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Measuring & Planning for Community & Climate Resilience

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MEASURING & PLANNING FOR COMMUNITY & CLIMATE RESILIENCE

By

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Thesis Co-Advisors: Adam Daigneault, Kathleen Bell, and Andrew Crawley

An Abstract of the Thesis Presented
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How communities respond to shocks has been of large interest to academics and governance since Hurricane Katrina in 2005, the Great Recession in 2008, and very recently the COVID-19 pandemic. The likelihood and extent of these shocks are ever increasing with the threat of climate change, leading to increased pressure on communities to understand and prepare for future shocks. Urban communities are often better prepared to strengthen their resilience due to the vast amount of resources they have available. Smaller, more rural communities typically have fewer resources to strengthen their resilience, making it harder to prepare for future shocks. This thesis analyzes community level resilience across Maine and the United States to assist communities in their preparation for shocks. My research focuses on measuring resilience at a community scale, in contrast to most resilience research done at a county level in the United States. In chapter 1, resilience scores were calculated by aggregating metrics believed to be correlated with community resilience. I found that resilience scores had significant correlations with urban/rural classifications and a communities dependency on natural resources, suggesting places with fewer resources to adapt to future shocks are the most susceptible. The second chapter focuses on aiding municipalities in the development of climate adaptation plans to best prepare for the future shocks of climate change. I developed two decision support tools

through literature review and applying the Delphi method. The first tool is the climate adaptation plan criteria list which aims to give municipalities concepts and topics that should be addressed in a thorough climate adaptation plan. The second tool is the climate adaptation and resilience outcome tool (CAROT) which aims to give examples to municipalities of how others have measured the success of their climate adaptation plans. Both tools highlight the varying topics that should be addressed with climate adaptation planning. Both chapters provide tools to analyze and strengthen community resilience. Overall, this work aims to strengthen communities' abilities to understand their vulnerabilities to shocks and build their community resilience towards future shocks. The tools and lists developed in each chapter are of use to all communities regardless of resource limitations but are of most use and importance to communities who are constrained in shock preparedness.

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CHAPTER 1

COMMUNITY RESILIENCE OF NATURAL RESOURCE DEPENDENT COMMUNITIES AND THE URBAN, RURAL DIVIDE

1.1 Introduction

1.1.1 Background

How communities respond to negative shocks, an event that causes an unwanted change in a community, has been especially relevant since Hurricane Katrina in 2005, the Great Recession in 2008, and very recently the COVID-19 pandemic (Cutter et al., 2014; Han and Goetz, 2015; Ringwood et al., 2019). This response to shock and the associated rebound can be important to understand as it affects long-term prosperity and sustainability of communities (Cutter et al., 2014). Resilience is an increasingly used term in recent literature and many papers have released different metrics for measuring how communities respond to shocks (Cutter et al., 2014; Johnson et al., 2018; Han and Goetz, 2015). The definition of resilience varies across academic disciplines and literature, but a very broad definition is "an ability to recover from or adjust easily to misfortune or change" (Merriam-Webster, 2022).

The origin of resilience research comes from the ecology space. Holling (1973) is the first researcher to use the language of resilience in academia and is often credited as the origin of most resilience research. He defines resilience as the ability of a system to absorb changes and still persist. This is in contrast to his definition of stability which he defines as the ability for the system to return to an equilibrium state after a disturbance. Other researchers have built upon the concepts Holling formulated to push resilience into other academic fields such as social and economic sciences (Dovers and Handmer, 1992; Adger, 2000; Rose, 2007).

Dovers and Handmer (1992) discuss human sustainability in the terms of global environmental change and brings Holling's definition of resilience into the human dimensions space. Adger (2000) expands on Dovers and Handmer's (1992) work by comparing social and ecological resilience in a framework of natural resource dependent communities (NRDC), using a case study of a Vietnam fishing village that has interacting aspects of social and ecological resilience that are discussed in the paper. Rose (2007) is arguably the first researcher to build resilience thinking into the economic space, discussing how to measure resilience in a dynamic way and enhance it in the economic sector. Following these papers that give conceptual frameworks for resilience in different spaces, researchers began to try to empirically measure resilience across larger geographic scales (Cutter et al., 2014; Johnson et al., 2018; Han and Goetz, 2015).

The first, most direct, approach that is used to measure resilience looks at the length in time in which a community is impacted by a shock before returning to a "normal" state. This is similar to Holling's (1973) definition of stability which is focused on the shock and the associated rebound (Holling, 1973; Han and Goetz, 2015). Numerous studies have taken this approach to dynamically measure the resilience of regions (Han and Goetz, 2015; Ringwood et al., 2019; Sensier et al., 2016).

Han and Goetz (2015) measured the economic resilience of counties across the United States during the 2008 recession. They did this by giving counties scores based on how much their economy (measured in unemployment) dropped and how fast they rebounded. Ringwood et al. (2019) approached United States resilience in a very similar way to Han and Goetz (2015) but paid specific attention to account for natural variation in county employment values. Similar research to Han and Goetz (2015) and Ringwood et al. (2019) has been done in Europe with similar success looking at measuring resilience through unemployment and gross domestic product (GDP) to place European regions into resilience categories being "resistant", "recovered", "not recovered but in upturn", and "not recovered and no upturn" (Sensier et al., 2016). These studies all look at data starting in 2007 to measure the resilience of places over time, using similar approaches.

Developing an indicator score is the second approach used (Cutter et al., 2014; Singh-Peterson et al., 2014). This score is composed of many metrics that are believed to be highly correlated with resilience and gives the user a static idea of how resilient a place is at a specific point in time. This score is often relative, and is used to compare communities to each other. For example, the level of education in a community is something that is generally considered to be correlated with resilience (Cutter et al., 2014; Han and Goetz, 2019; Singh-Peterson et al., 2014). The ideology behind this is if a large percentage of the population is educated, then there are likely to be more entrepreneurs, employers are more likely to move to the area, and the workforce is more skilled. For these reasons, common literature usually includes measures of education in their resilience indicator lists (Cutter et al., 2014; Singh-Peterson et al., 2014). This thought process is usually repeated to develop a list of indicators that measure resilience across multiple attributes/domains.

Most papers that use an indicator based approach originate from Cutter et al. (2010) Baseline Resilience Indicators for Communities (BRIC) framework which predicts community resilience across social, economic, community capital, institutional, housing/infrastructural, and environmental metrics. Singh-Peterson et al. (2014) reworked and adapted Cutter et al. (2010) BRIC framework to the Sunshine Coast in Australia and compared it to other predictors and models used in their region. Singh-Peterson et al. (2014) suggests that Cutter et al. (2010) BRIC framework can be used as a baseline framework for developing case-specific indicators. Beccari (2016) compiled numerous studies within the disaster preparedness and resilience indicator space to assess the most commonly used metrics across the literature. There is also additional literature that has focused on making the static approach of measuring resilience using metrics more dynamic by measuring resilience at two different points in time and comparing across (Cutter and Derakhshan, 2020). This approach adds more flexibility to the approach and allows for understanding of the direction in which a community might be transitioning in the future.

These two approaches have different purposes and flaws. Measuring the length of a shock can only look at historical events, and using how resilient a place was in the past can lead to false predictions of the future. If for example, a community lost a large employer since the 2008 recession, the resilience they had in 2008 will not predict how resilient they are now without that major employer. Data requirements are also an issue as gathering data at the frequency required to measure shock lengths is often highly resource intensive (Rose, 2007). The resilience indicator approach does not have any limitations in terms of years available as whenever data is posted the resilience score can be updated. This approach is less resource intensive than the shock length method as in its simplest form only data from one time period is required (Rose, 2007). An indicator approach can also give you information on more than just economic resilience, branching into other disciplines like natural disaster preparedness, which is becoming increasingly important with climate change (Cutter et al., 2014; Johnson et al., 2018). However, the main flaw with the indicators approach is that it does not directly measure resilience and rather measures variables we expect to be correlated with resilience.

Cutter et al. (2016) took an approach to studying rural resilience by looking at how population density of counties impact BRIC scores. They looked at how mainly rural and urban counties in the United States differed in levels or resilience and found statistical differences in their corresponding BRIC scores. They accounted this to rural areas often lacking the resources, businesses, and adequate government allocations to rebound after a shock (Cutter et al., 2016). This is in comparison to urban places that have a large wealth of human capital, making them more resilient (Cutter et al., 2016). At the same time, however, rural communities are more self-reliant, and if they have a strong sense of community this can outweigh some of the drawbacks of the lack of human capital that rural areas have (Cutter et al., 2016).

Despite differing alternatives to measuring resilience, most methods in the US use county-level data. This is largely due to community level data being scarce and inconsistent (Cutter et al., 2016). At a community level, there are fewer potential indicators to measure resilience due to less data being available. Where this becomes a problem is when a county is very large and has communities that differ greatly across the resilience measurements. For example, in Penobscot County, Maine the southern portion of the county is home to Bangor, Maine which is one of the larger metropolitan areas in the state, while the northern portion of the county is fairly rural. The resilience of these places are likely significantly different which county data does not represent. Measuring resilience at a community level, despite its difficulties, allows for a more thorough look at how resilience varies across a landscape.

There have been many studies that measure the resilience of United States counties using interdisciplinary metrics (Cutter et al., 2014; Han and Goetz, 2015; Ringwood et al., 2019; Sensier et al., 2016). However, few have measured resilience in the United States at a sub-county level to understand differences across communities that are either urban or rural or are very natural resource dependent. In this thesis, I will use an indicator based approach to measure community resilience across the United States in 2018. This approach was chosen over historical measures due to it being able to measure more than just economic resilience as well as it not requiring temporal data which is difficult to obtain at a community level. This approach will let us answer questions that county level data has a hard time answering. There are two objectives of this chapter. The first is to measure community resilience across the United States using an indicator approach. The second is to analyze how these resilience scores vary across the landscape depending on natural resource dependency and an urban/rural threshold.

1.2 Methods

This section details the building of the community level resilience index. Community is defined in this paper at the county subdivision level. County subdivisions are community areas focused on trading centers and or major land use areas (United States. Bureau of the

Framework
Center of Disease Control Social Vulnerability Index
Baseline Resilience Indicators for Communities (BRIC)
Katahdin Indicators
Community Resilience Indicator Analysis
Location Affordability Index
Maine Lifeline and Social Vulnerability Index
Maine Measures of Growth Report
Area Deprivation Index (ADI)

Table 1.1. The eight frameworks that resilience metrics were pulled from. For more detailed citations, see the appendix where the sources are listed in the same order.

Census, 1994). They are smaller than counties but are often larger than census bureau tracts. This level of space was chosen due to the factors discussed in the introduction.

1.2.1 Metric choice

Resilience metrics were chosen based on the commonality of the metrics in literature, how unique it was among the other metrics found, and if the data was available at a county subdivision level. A literature review was done of resilience index frameworks. A total of eight papers/frameworks were examined which can be found in Table 1.1. The citations for these papers/frameworks can be found in the appendix. Information was gathered on where metrics overlapped across literature, where the data came from, the spatial scale of the data, as well as the relationship the metric has with resilience. A list of the metrics that were discussed by three or more sources can be found in the appendix in Table A.1.

1.2.2 Data sources

The metrics that were chosen for the indicator list were compiled from 5 data sources. The data was widely available at a county subdivision level. All data sources were free to access. The five sources are detailed in Table 1.2.

Number	Dataset	Data Provider
1	American Community Survey 5-year Estimates	Census Bureau
2	Fixed-Broadband-Deployment-Data	Federal Communications Commission
3	National Land Cover Dataset	US Geological Survey
4	Protected Land Dataset	US Geological Survey
5	Resilient Land Mapping Tool	The Nature Conservancy

Table 1.2. The five data sources from which the resilience index was built.

1.2.3 Data pre-processing

Once the data were acquired from the various sources they went through a series of transformations depending on the specific metric. Most metrics needed to be converted to a percentage to equalize places with varying population sizes.

The next transformation that was applied to every metric was normalization. Normalization is referring to the technique of scaling a dataset from its original range to a range of 0 to 1. This is done by assigning the minimum value in the range to 0, the maximum value to 1, and scaling the rest of the numbers in between. The scaling works by taking each observation and subtracting the minimum value and then dividing it by the range. Normalization is a fairly common approach in indicators research (Cutter et al., 2014; Singh-Peterson et al., 2014). It makes the weight of each indicator in the resilience score be the same as they all have the same range. It also makes variables easily comparable. One significant downside to normalization is that the values lose all meaning outside of comparison.

The final transformation applied to some indicators was the inversion of the normalized values. This inversion was applied to indicators that are believed to have a negative relationship with resilience. These indicators would suggest a higher level of resilience when they are lower. An example would be unemployment rate. This value needs to be inverted so that a low value would represent low resilience and a high value would represent high resilience. This was done by subtracting the normalized values of relevant indicators from 1. The indicators and transformations are shown in the resilience index list in Table 1.3.

1.2.4 Development of the community resilience index

Thirty indicators from the initial literature review were organized into 4 categories: human well-being/cultural/social indicators, economic/financial indicators, infrastructure indicators, and lastly environmental/natural indicators. The categories are to ensure that when calculating the total resilience score, one type of resilience (e.g human well-being/cultural/social or economic/financial) is not represented more than another due to it having more indicators.

A correlation test was run to determine if any of the metrics had high collinearity with other metrics. Metrics that have a high correlation with others suggest that the variable is not measuring something unique from the other variables, and is weighting what it is measuring more in the final list. In an extreme case, if unemployment rate and employment rate were both included in the economic/financial indicator list, they collectively would not bring much unique information to the resilience score. Rather, they would make the level of employment in the county subdivision be worth twice as much as the other metrics. Ultimately, metric choice was subjective however, the collinearity of metrics was highly considered in the selection of the final list.

Cronbach's alpha scores also impacted metrics choice. Cronbach's alpha tests if a group of indicators fit well together and measures the same concept (Cronbach, 1951). A higher value means a larger internal consistency between the metrics. Internally consistent results would suggest that metrics are measuring the same concept. As discussed earlier, it is best to avoid having variables that are correlated with each other as it would double count that concept of resilience. If metrics that are highly correlated with other metrics are dropped the Cronbach's alpha value would be smaller. Therefore, the impact of metric removal on the Cronbach's alpha score was also considered in the final metric choice.

The final indicator list consisted of 24 metrics. These metrics are shown in Table 1.3. A correlation matrix of the indicator list can be found within the appendix in Figure A.2.

The Cronbach's alpha scores for the four resilience categories and the total list can be found in Table 1.4. The four resilience categories were not internally consistent.

1.2.5 Calculating scores

The final list was normalized such that values in each resilience category were averaged together to give an average resilience score in each category for each county subdivision. Once all values were calculated for the four categories these values were averaged together to give each county subdivision a total resilience score where 0 corresponds with low resilience and 1 corresponds with high resilience. This method was done to give equal weight to each of the four categories. However, other methodologies were later tested and are discussed in Section 1.2.8.

1.2.6 Data limitations

Alaska and Hawaii were not included in the study due to missing data. Numerous observations were also lost due to missing data at the county subdivision level. 10,010 observations were lost from missing ACS data at a county subdivision level. This data was overwhelming lost from the rural portion of the sample due to data suppression in county subdivisions with smaller populations (Bureau, 2021). Data suppression is referring to censoring data of small populations to protect individuals' identities. To see which metrics had the most data loss due to data suppression see Table A.3. 4,200 observations were dropped because of challenges encountered completing the GIS analyses required to measure some metrics. With more time and advanced GIS support, these challenges could be addressed. However, that level of analysis was beyond the scope of this research. With more time these observations could be gathered through other means. This resulted in a final sample size of 21,286 county subdivisions.

Indicator	Correlation	Dataset
Human well-being/cultural/social indicators		
Working age population (ages 20-65)*	+	1
Health insurance coverage*	+	1
Population with high school degrees*	+	1
People who speak English "less than well"*	-	1
Population change 2000-2018*	-	1
Mean advertised max broadband download speed	+	2
Economic/financial indicators		
Unemployment rate	-	1
Median household income	+	1
Mean commuting time	-	1
Service occupations*	-	1
Arts; entertainment; and recreation; accommodation & food services*	-	1
Households with social security*	-	1
Households with public assistance income*	-	1
Gini index of income inequality	-	1
Gender income inequality	-	1
Infrastructure indicators		
Owner-occupied housing*	+	1
Households with no vehicle available*	-	1
Median housing value	+	1
Housing occupancy rate*	+	1
Median monthly gross rent	-	1
Environmental/natural indicators		
Land in wetland*	+	3
Percent impervious land	-	3
Public open space (parks, community forest, etc.)*	+	4
Recognized biodiversity value*	+	5

Table 1.3. The metrics making up the resilience index with their correlations, and data sources. * signifies that the metrics is a percentage of the total in the county subdivision.

Resilience Category	Cronbach's Alpha
Human Well-Being/Cultural/Social	0.532
Economic/Financial	0.433
Infrastructure	0.297
Environmental/Natural	0.011
Total	0.321

Table 1.4. Cronbach alpha scores for the four resilience categories and the total list.

1.2.7 Statistical tests

T-tests and analysis of variance (ANOVA) were used in this analysis to compare across different subsetted samples. T-tests were performed to understand if natural resource dependent communities (NRDC) and rural places have statistically different resilience scores than their counterparts. ANOVA was used to determine which samples had the largest differences. NRDCs were defined by the percentage of their employment within agriculture; forestry; fishing and hunting; and mining. Rural communities were defined by their population size.

Thresholds were used to subset the county subdivisions into natural resource dependency samples and urban/rural samples. A sensitivity test was performed around these thresholds to test if the results changed based on the threshold used. Multiple studies define the threshold for natural resource dependency at different levels by the percentage of employment within agriculture; forestry; fishing and hunting; and mining. Bender et al. (1985) used a level of 20%, Stedman et al. (2005) used a level of 10%, and the Economic Research Service (2019) used a value of 8%.

The definition of a rural and urban place also differs among literature. The Census Bureau generally defines a rural community as a place with a population less then 2500. Less than 2500 people is the most common definition of a rural place, however, other organizations use different definitions for different tasks. The USDA Community Facilities define rural places as places with populations of less than 20,000 people. While often times research will define places with populations less than 50,000 as a non-metro place (Cromartie and Bucholtz, 2008). All three of these thresholds were analyzed as the definition of the urban/rural divide. Outside of the threshold analysis, greater than 8% of employment in agriculture; forestry; fishing and hunting; and mining was used for the NRDC definition, and greater than 2500 people was used as the urban definition.

1.2.8 Sensitivity analysis

Some evaluation was done outside the core analysis to test the sensitivity of our results. That is, given different assumptions or methodologies do the results remain true? Two key sensitivities were tested. The first gave each metric in the community resilience index equal weight as opposed to giving each category equal weight. This was done as both approaches have their advantages and disadvantages. The categorization approach does not weigh one aspect of resilience more than another, and the amount of metrics in a category does not impact its weight. With an equal weight to each indicator approach categories with more metrics are weighted more in the final score. The main driver behind which approach to use is how important individual metrics are valued in comparison to different aspects of resilience as a whole.

The second sensitivity analysis tested was removing the environmental indicators from the score calculation. This was done due to the large uncertainties around the environmental indicators. The environmental category had numerous missing values leading to a decline in the total observations observed. There are also known issues with measuring environmental resilience through an indicator approach. There is a lack of accurate data that gets at environmental resilience concepts which leave many proxies to be used instead (e.g wetlands for natural buffers, impervious surfaces for water retention) (Cutter et al., 2014). This issue is amplified at a county subdivision scale where fewer metrics are available.

1.3 Results

The spatial distribution of the resilience scores can be seen in Figure 1.1. This map shows how the resilience scores vary across the United States. Due to the normalization process, resilience scores are reported from low to high as the values themselves have no meaning outside comparison. The map also is useful in the identification of areas with large data losses as well as the variation of sizes of county subdivisions across the United States. Similar maps were generated for the four resilience categories to see spatial variations across the different aspects of resilience. These maps can be seen in Figure 1.2.

There is an interesting distribution of resilience across the landscape. Coastal urban areas have higher levels of resilience across the United States. Most notably the northeast megalopolis, coastal areas around the Gulf of Mexico, and the urban areas of California. There also are high resilience levels in rural areas of the western deserts and Oklahoma. This is largely due to the environmental resilience category. These places have very low levels of impervious surfaces, and large public lands (bureau of land management lands, reservations, forest service land). The extreme distribution of environmental metrics in the west are showcased in Figure 1.2. There are also very large resilience levels found across the southeastern United States within the environmental category.

In terms of the other categories social has fairly stark differences between the northern and southern United States. The main driver of this is likely the "People who speak English 'less than well'" metric which has significant regional differences. There is no noticeably large differences across either the economic or infrastructure category maps. These variations stress the importance of comparing across regions rather than at national levels when making resource allocation decisions.

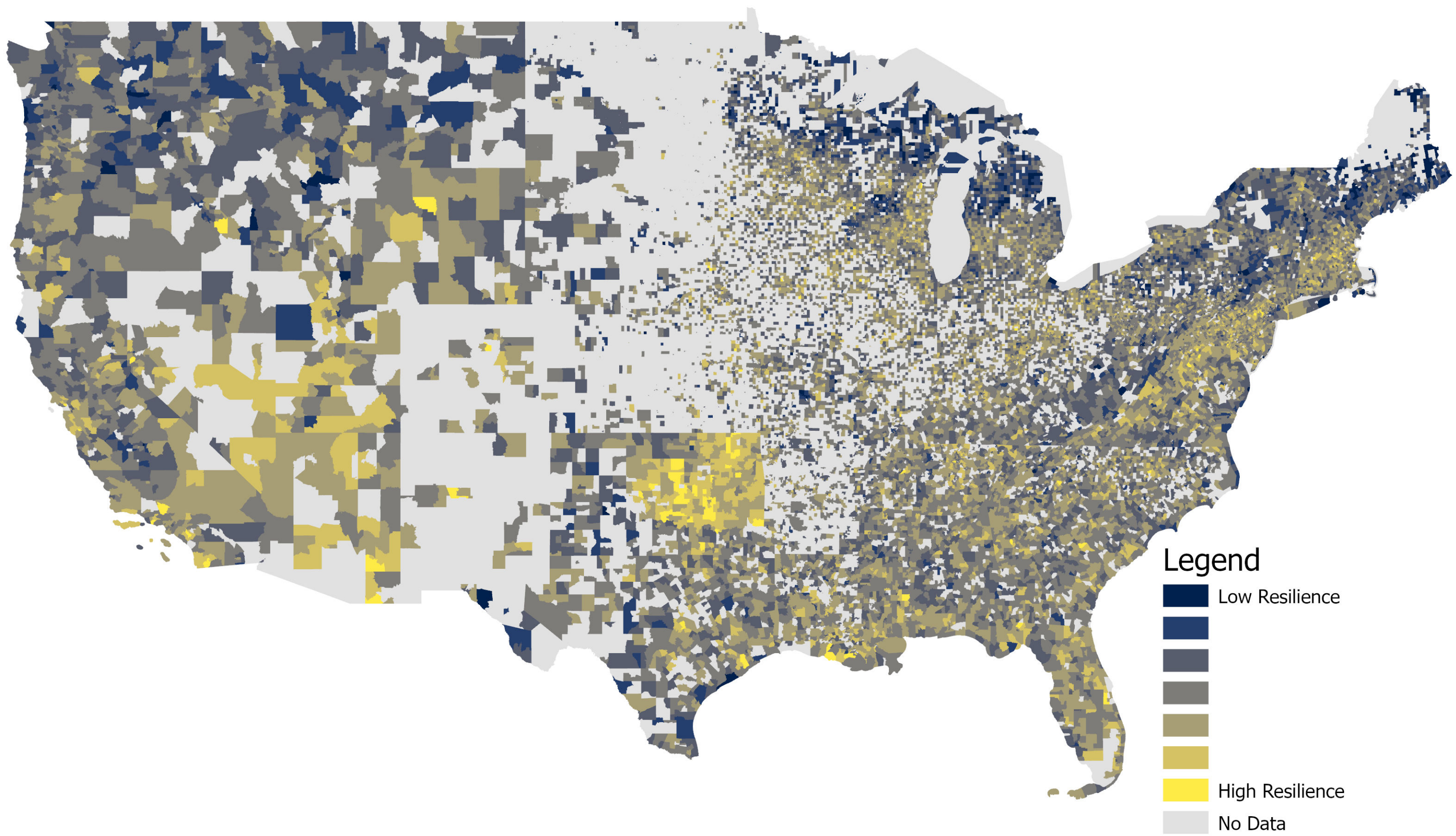

Figure 1.1. The spatial variation of county level resilience across the United States (n=21,286). Scale is represented in 0.5 standard deviation intervals.

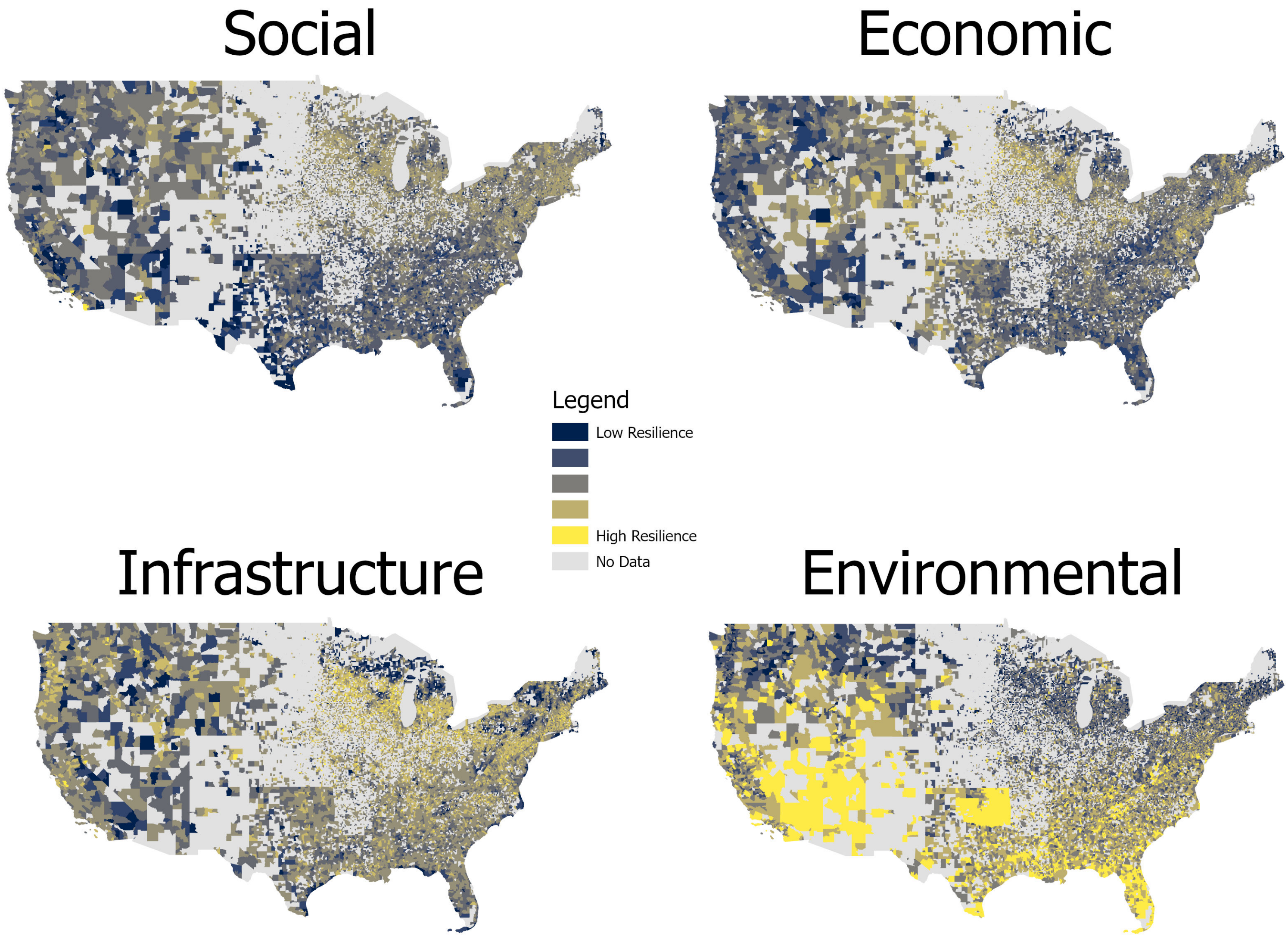

Figure 1.2. The spatial variation of county level resilience across the United States split into the four resilience categories (n=21,286). Scale is represented in 0.5 standard deviation intervals.

Variable	Mean	Median	Standard Deviation
Total Resilience Score	0.567	0.568	0.029
Social Resilience Score	0.704	0.708	0.027
Economic Resilience Score	0.707	0.707	0.028
Infrastructure Resilience Score	0.580	0.590	0.065
Environmental Resilience Score	0.276	0.273	0.087

Table 1.5. Summary statistics for the five variables of interest (n=21,286).

The summary statistics for the scores of interest are listed in Table 1.5. At the urban/rural threshold of 2500 people, urban places ($M_U = 0.572$) were significantly more resilient then their rural counterparts ($M_R = 0.560, P = 2.2e^{-16}$). Across the 20,000 people threshold and the 50,000 people theshold these results stayed consistent ($M_U = 0.574, M_R = 0.566, P = 2.2e^{-16}$ and $M_U = 0.574, M_R = 0.567, P = 2.2e^{-13}$ respectively).

At all NRDC thresholds (8%, 10%, and 20%), NRDCs were significantly less resilient than their non-NRDC counterpart. This corresponds with the mean resilience scores of NRDCs being 0.563, 0.563, and 0.560 and their counter-parts mean resilience scores being 0.568, 0.567, and 0.567 respectively. The P-values were 0.041, 0.022, and 0.000 respectively.

These differences can be seen in Figure 1.3. The largest differences are seen with the urban/rural threshold with a notable difference across natural resource dependency at a less significant level. This relationship held true in the two-sample ANOVA analysis. Both of the factors had statistically significant levels of variation having the same P-value being $2e^-16$. However, the urban/rural F value was significantly higher than the NRDC F value being 807.52 to 67.74 respectively. This suggests that the variance between groups is much larger in the urban/rural sample than in the NRDC sample.

The difference in resilience scores between urban and rural places was mainly driven by the differences in infrastructure and environmental scores. Urban places had significantly higher resilience scores within those two categories. With mean urban infrastructure scores being 0.588 and the rural mean being 0.570 ($P = 2.2e^{-16}$). Rural places had higher

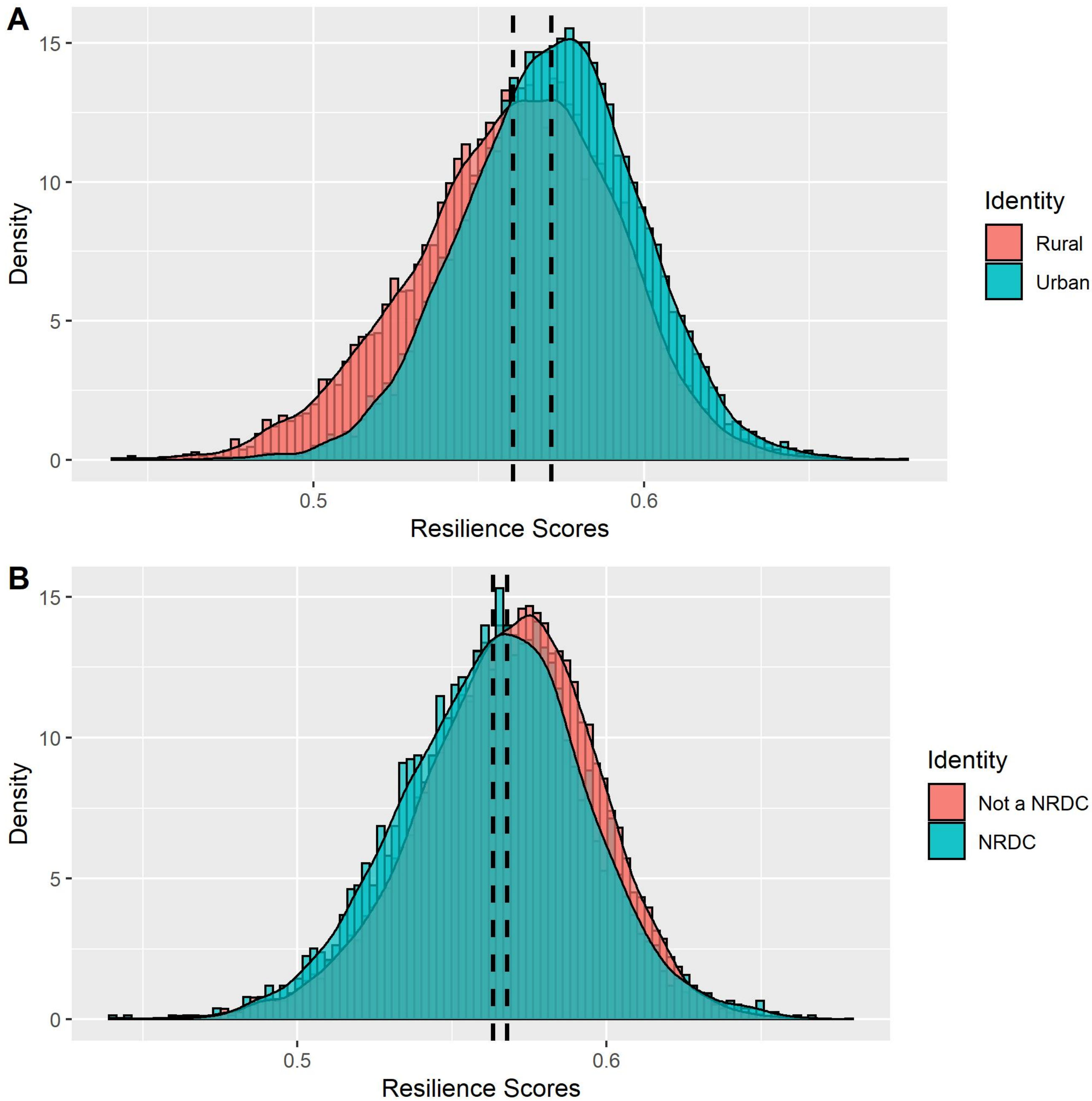

Figure 1.3. Histogram, density plot, and means values (dotted lines) for the urban and rural samples (A) and across the natural resource dependency threshold (B) (n=21,286). The urban and rural means are 0.572 and 0.560 respectively. The NRDC and non-NRDC means are 0.563 and 0.568 respectively.

owner-occupied housing and significantly lower rent values. However, urban places made up for these differences with much higher housing values and housing occupancy rates. The environmental means are 0.291 and 0.259 respectively ($P = 2.2e^{-16}$). All the environmental metrics besides public open space were higher in urban areas. The category where rural places have higher resilience is the social category where the urban mean is 0.703 and the rural mean is 0.705 ($P = 1.4e^{-10}$). The largest variation upon these samples was within the percentage of people who speak English "less than well" metric. The rural value for the variable was significantly higher than the urban value. Rural places had significantly larger economic resilience scores at P=0.05 which is not nearly as significant as the other tests, but still significant. The urban mean for social is 0.706 and the rural mean is 0.707 ($P = 0.036$). There were variable differences across the economic metrics but no large noticeable differences.

NRDCs have significantly larger economic resilience scores. The mean economic resilience score in NRDCs is 0.710 with a mean of 0.706 in the other sample ($P = 2.2e^{-16}$). This is largely due to the metric used to determine natural resource dependency. Because more individuals are hired in agriculture; forestry; fishing and hunting; and mining less people are hired in arts and service occupations. When these metrics are removed NRDCs have lower economic resilience scores. The main drivers of this are household income and lower households with social security. Non-NRDCs have significantly larger social and infrastructure resilience scores. The mean social resilience score in NRDCs is 0.693 with the other sample's mean being 0.706 ($P = 2.2e^{-16}$). All metrics except for population change had a higher level of resilience in non-NRDCs in comparison to the other sample. The infrastructure means are 0.572 and 0.582 respectively ($P = 2.2e^{-16}$). Median monthly gross rent was the only infrastructure metric that showed higher resilience in NRDCs. The environmental resilience scores were not statistically different ($P = 0.885$). Both samples have the same mean of 0.278.

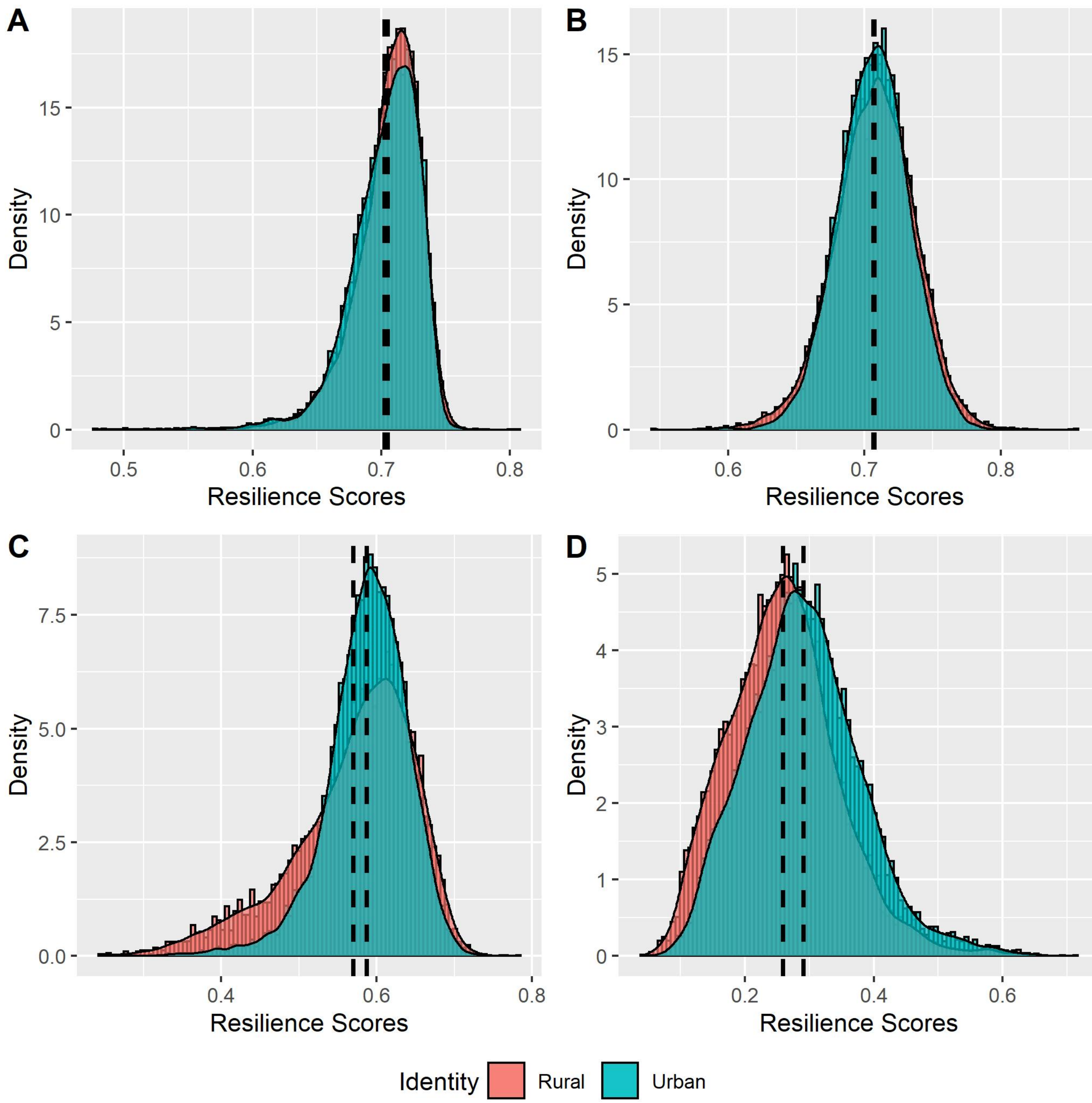

Figure 1.4. Histogram, density plot, and means values (dotted lines) for the urban and rural samples separated into the four metric categories social (A), economic (B), infrastructure (C), and environmental (D) (n=21,286).

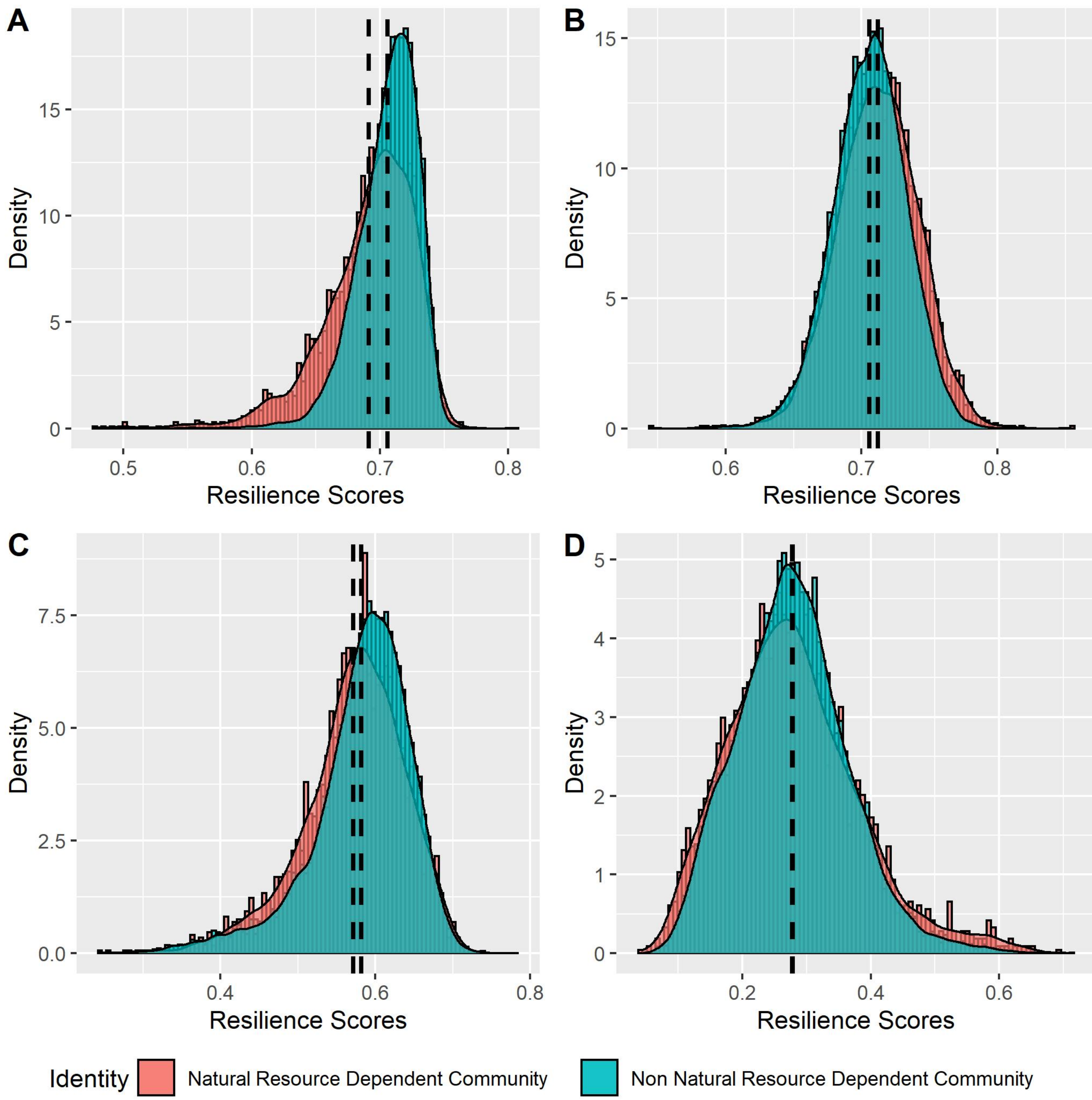

Figure 1.5. Histogram, density plot, and means values (dotted lines) across the resource dependency threshold separated into the four metric categories social (A), economic (B), infrastructure (C), and environmental (D) (n=21,286).

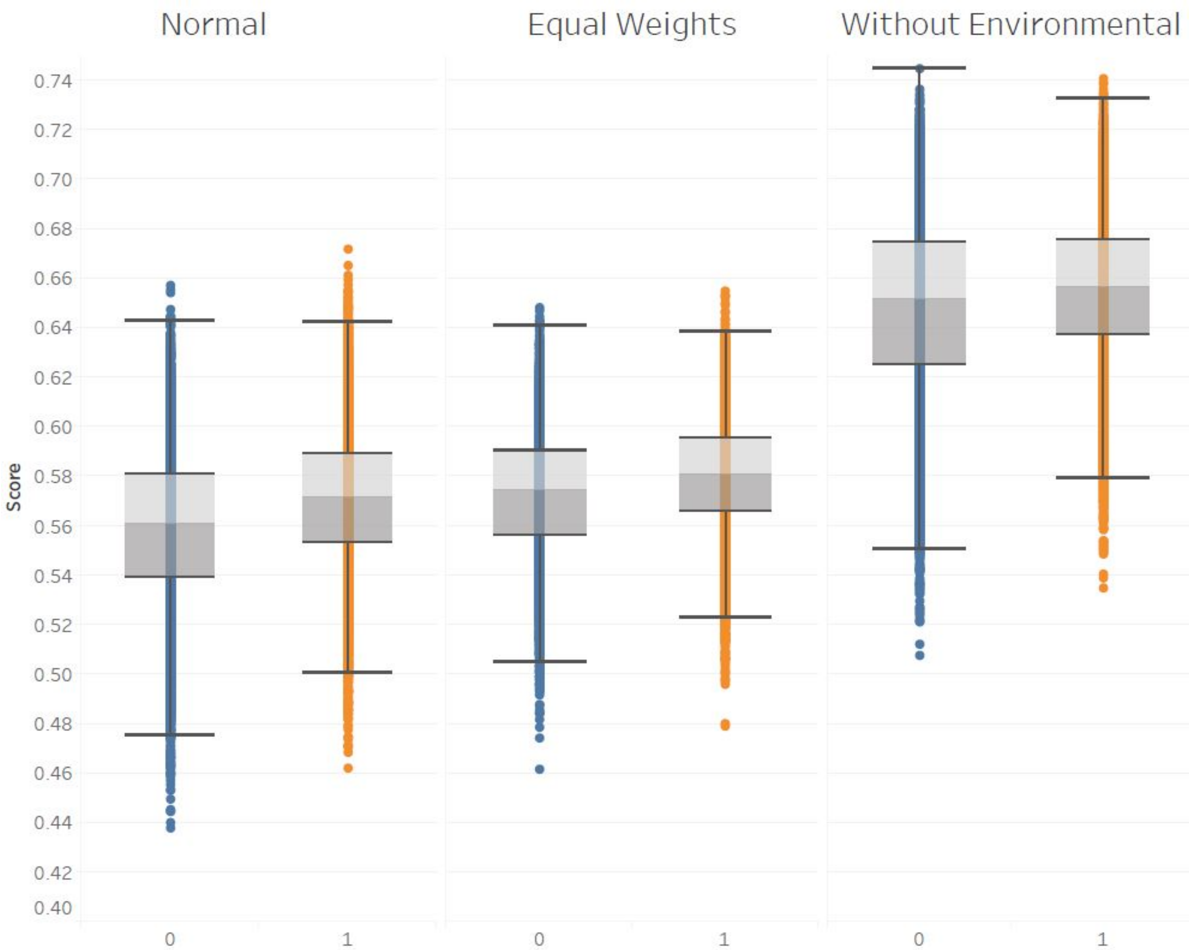

Figure 1.6. Box and whisker plots for the urban and rural samples showing the distributions of the scores under different assumptions. 1 is urban and 0 is rural (n=21,286 for normal and equal weights, n=25441 for without environmental).

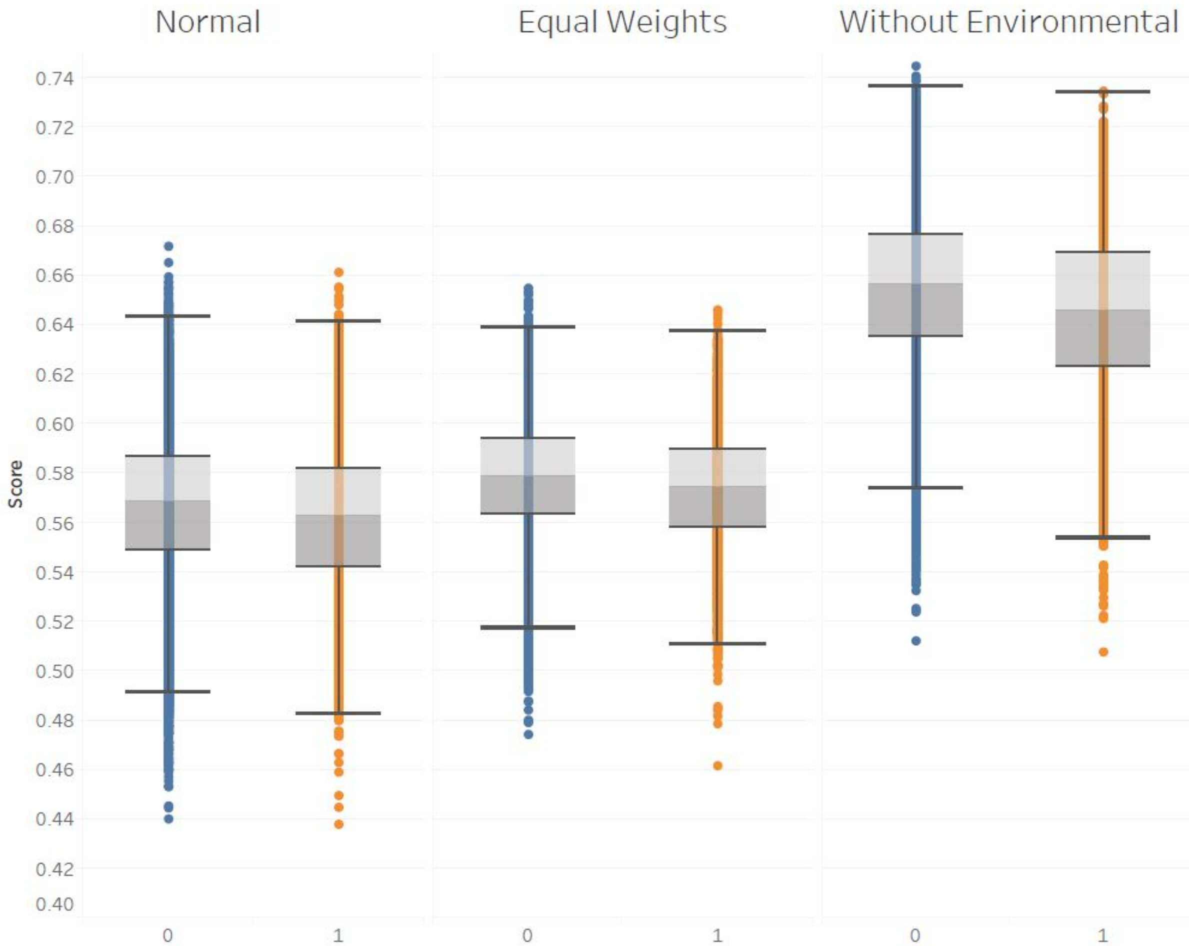

Figure 1.7. Box and whisker plots across the natural resource dependency threshold showing the distributions of the scores under different assumptions. 1 is NRDC and 0 is non-NRDC (n=21,286 for normal and equal weights, n=25441 for without environmental).

1.3.1 Sensitivity analysis

The core results were consistent across the different sensitivities tested. This can be seen in Figure 1.6 and 1.7, where the distributions under different assumptions are shown across the samples. When the environmental category was dropped the scores were significantly higher. This is due to the environmental scores averaging around 0.28 which brings down the mean resilience score when included.

The results across the urban/rural ($P_{2500} = 2.2e^{-16}, P_{20000} = 2.2e^{-16}, P_{50000} = 1.6e^{-6}$) and natural resource dependency ($P_{0.08} = 2.2e^{-16}, P_{0.10} = 5.6e^{-15}, P_{0.20} = 9.2e^{-9}$) thresholds stayed the same with slightly different but still highly statistically significant results when each metric was given equal weight. The ANOVA resulted in F values still suggesting larger differences between the urban, rural samples then the NRDC, non-NRDC sample being 395.16 ($P = 2.2e^{-16}$) and 98.59 ($P = 2.2e^{-16}$) respectively.

Urban places had statistically larger resilience scores at the 2500 ($P = 2.2e^{-16}$) and 20,000 ($P = 7.2e^{-7}$) people threshold when the environmental category was removed. In contrast to the normal resilience scores, at the 50,000 people threshold, there was no statistically significant difference between the samples ($P = 0.1543$). Non-NRDC's had statistically larger resilience scores at all threshold levels ($P = 2.2e^{-16}$ at all levels). The ANOVA also had statistically significant differences across both samples. In contrast to the normal resilience score, the F value for the natural resource dependency threshold was much higher at 269.62 ($P = 2.2e^{-16}$) in comparison to the urban-rural F value of 24.08 ($P = 9.3e^{-7}$). Thus, there were larger differences seen across the natural resource dependency threshold in comparison to the urban/rural threshold when the environmental category was removed.

1.4 Discussion

The community resilience index list developed in this chapter could be used by larger state and regional governments to determine where to allocate resources to build resilience across their geographic area. The resilience scores are of most use in comparing similar county subdivisions to each other looking at their relative scores in each category. Relative resilience is in reference to the normalization process which removed any true meaning from the values outside of ranking them in comparison to each other within the same range (0-1). Due to this important step in the process of giving communities scores, there is no threshold to label a community as resilient or not within a specific category. Further, no specific rule can be made around the 0-1 range as the mean values within those ranges differs greatly between categories.

The preferred method for a government to assess the weaknesses and strengths across their geography using the community resilience index list is by looking at how the communities compare in each category across their region. For example, if some hypothetical community is in the top 25% of social scores across the state but within the lower 25% of economic scores in the state, resources should be allocated to improve their economic resilience as they have a comparatively lower level of resilience. The results highlight that the community resilience index does not necessarily work consistently across the United States which is why comparing values at a county or state group can be more useful than looking at the nation as a whole. For example, in places like southern Florida and California the amount of people who speak English "less than well" is not as relevant to the resilience score calculation due to the large Spanish speaking population in those parts of the United States. Therefore, comparing across a region can control for regional differences in scores and should be the focus of future community level resilience work.

Testing for sensitivities was a crucial step of this process. It highlighted that despite the different weights given to each metric, the results hold true. The environmental sensitivity test also brings attention to the environmental resilience category and how it impacted the statistical results of this study. Despite a majority of the results staying the same, removing the environmental category made natural resource dependency the larger significant driver of resilience within the ANOVA, compared to rural/urban. The overall relationship between resilience across the thresholds examined stayed the same but the magnitude differed and the urban/rural threshold relationship was less strong. This follows the initial results that showed the environmental category having large differences across the urban/rural threshold. The sensitivity of the results signifies how the resilience index list is purposely meant to be broad and case-specific resilience metrics could be chosen for specific instances. For example, Singh-Peterson et al. (2014) uses Cutter et al. (2014)

BRIC framework as a stepping stone for building their own specific list. Cutter et al. (2014) BRIC framework, as is stated in its label, is a baseline and should be adapted for specific cases. Similar work should be done at a community scale when building a resilience framework, as the list should adapt to the region being studied to fit the specific needs of the research team.

I use the vague term "allocate resources" to describe steps taken by communities to increase their resilience to a variety of shocks. The direct way to increase their resilience score is to impact the metrics for which the scores are calculated. Some metrics are extremely actionable and should be interpreted as a way to allocate resources to strengthen resilience in a community. Metrics like "population with high school degrees" and "mean advertised max broadband download speed" are examples of metrics that can be directly targeted by communities to increase their resilience. Strengthening these metrics will increase their resilience while simultaneously increasing their resilience scores and relative rank. Policies should be acted upon based on the number of metrics that will be impacted, as well as which categories are in need of strengthening.

In terms of the analysis portion of this paper, the results show similar differences to Cutter et al. (2016). As in urban places had larger resilience scores than their rural counterparts. The significant drivers for these differences are the infrastructure and environmental categories as shown in Figure 1.4. Higher infrastructure scores in urban places follow intuition given that urban places have more people, more money, and are usually more densely populated. Given the same intuition environmental scores would be expected to have the opposite correlation with a place being urban. This was a surprising outcome of the study and is the opposite of the county level results of Cutter et al. (2016). This is likely due to the limitations of the environmental indicators in most resilience research and specifically at the county subdivision level. Other researchers have signified the limitations of measuring environmental resilience and the difficulties of finding accurate measures (Cutter et al., 2014). This issue is amplified at a county subdivision level where most metrics either exist at any spatial scale (the metrics used here) or at the county level.

Social resilience is higher in rural places which is likely due to these places having a stronger sense of community and being more self-reliant. Economic resilience showed no large significant differences across the samples. This lack of differences in economic scores balances out the higher wages and economic productivity of urban places with their economic inequality.

All the categories showed NRDCs to be less resilient besides the environmental metric which showed no significant differences when metrics that are correlated with the threshold metric were removed. This analysis strengthens the argument that NRDCs are on average less resilient (Cutter et al., 2014; Adger, 2000). However, the ANOVA tests suggest that despite natural resource dependency having a large impact on resilience scores, the main driver of this relationship is the tendency for these places to be rural, leading to lower levels of resilience. In comparison to rural communities, NRDCs have larger environmental scores, suggesting larger environmental quality in places with rich natural resources. NRDCs also have lower social scores than just rural places being led by metrics like lower high school graduates, English proficiency, and health care. A lot of natural resources dependent communities often rely on low skill labor with limited high paying job opportunities outside of the sector, which would decrease social and economic scores alike.

These results suggest that rural places with fewer resources are more susceptible to shocks. Policy makers should take this into consideration when deciding where to allocate state and federal resources for resilience building. Rural places have smaller populations, less governmental resources, and are often the most susceptible to shocks.

There are a few key limitations to the community resilience index and its applications across the United States beyond what was previously discussed. Firstly, the concept of resilience is abstract. Using metrics believed to be correlated with resilience gives a best guess of resilience but does not by any means directly predict it. This biasness of metric choice was minimized through the literature review and correlation tests, but in no way does it not exist. Secondly, due to the spatial scale selected, 28% of county subdivisions were lost due to ACS 5-year estimates data suppression. This is unavoidable at this scale and comes into significant play in the rural subset of the sample as places with smaller populations are more likely to have values be individually identifiable. This was an issue, as 46% of the rural sample was lost to data suppression while only 1% of the urban sample was lost to data suppression. Another flaw of using ACS 5-year estimates at this level is the standard errors associated with rural estimates are usually large. The ACS 5-year estimates use 5 years of sampling in communities to estimate values. In rural areas, there are fewer people to be surveyed resulting in larger standard errors (Greiman, 2017). This is unavoidable given the geographic scale of this study, however, it adds more validity to county level research as the standard errors are significantly lower.

Future research should look into temporal impacts of the community resilience index. Understanding how these scores change after a shock like the COVID-19 pandemic can be useful for understanding how well the index has predicted resilience across the United States. More research should also look into expanding the community level environmental index to better measure environmental resilience. Lastly, due to national variation in metrics research should focus on how the results vary at a regional scale rather than nationally.

1.5 Conclusion

Measuring community level resilience is important to understand how resilience varies over a landscape. This work enables governments to assess the levels of resilience across their geographic area and gives quantifiable reasoning for resource allocation. The community resilience index was constructed in this process through literature review and refined with correlation matrices, Cronbach's alpha, and peer feedback. This tool was used to assess diverse definitions of resilience across the United States and look at differences across the urban/rural divide and natural resource dependency thresholds. Overall, rural and NRDCs were found to be significantly less resilient than their counterparts. However, the urban/rural divide was the larger determiner of resilience across the sample. This research builds a baseline resilience index to be used across the United States and stresses the importance of assessing weaknesses within communities before making resilience strengthening decisions.

CHAPTER 2

DEVELOPING DECISION SUPPORT TOOLS FOR MAINE'S CLIMATE CHANGE ADAPTATION PRACTITIONERS

2.1 Introduction

The Maine Scientific and Technical Subcommittee (STS) recommends that the Maine Climate Council (MCC) prepares to manage for 3 feet of sea level rise by 2050 and 8.8 feet of sea level rise by 2100. These predictions for sea level rise come from estimates that Maine could warm an additional 2-4°F by 2050 with some estimates saying 10°F by 2100 (Fernandez and Marvinney, 2020). How Maine communities prepare for these changes is of great debate among organizations like the MCC and the Governor's Office of Policy and Innovation (GOPIF).

There are limited examples of climate adaptation plans being organized and being implemented across the state of Maine. Some of these include Portland and South Portland's One Climate Future and York's Climate Action Plan (Krulik et al., 2020; Town of York, 2021). These communities have the wealth of resources to be able to research and create plans to address future climate concerns. Smaller communities, with fewer resources, people, and time are already stretched thin in terms of municipal planning. Preparing for climate change, despite being one of the largest threats to these communities, is often not the number one priority due to their limited resources (Carter and Culp, 2010; Homsy and Warner, 2013).

A wealth of research has found disadvantaged groups will suffer disproportionately more from the adverse effects of climate change (Reckien et al., 2017; Thomas and Twyman, 2005; Coggins et al., 2021). This category includes smaller towns and municipalities that will similarly suffer disproportionately more from climate change because they do not have the money or resources to successfully adapt (Anthoff et al., 2007; Hsiang et al., 2019).

This chapter's goal is to address these issues and give communities decision support tools to make the complex resource intensive task of climate change adaptation less far out of reach. Two decision support tools are developed to assist Maine municipalities in climate adaptation. These tools are part of a larger framework designed to help Maine municipalities prepare for climate change.

The first decision support tool developed is the climate adaptation criteria list which is compiled of criteria that should be included in a climate adaptation plan. The list guides users in the building of a climate adaptation plan. Numerous authors have identified what qualities make a climate adaptation plan good. Tang et al. (2010) analyzed forty local climate adaptation plans across the United States and ranked their quality by scores assigned to "Awareness", "Analysis", and "Action" indicators. Woodruff and Stults (2016) did a similar type of analysis, ranking climate adaptation plans for forty-four United States cities using seven plan quality principles ranging from goals, to uncertainty, to coordination, made up of numerous indicators. Berke and Godschalk (2009) performed a similar study to the one carried out in this chapter doing a meta-analysis of plan quality papers, determining what researchers value in municipal planning. They identified numerous trends within research and established that plan evaluation will become more important in the future (Berke and Godschalk, 2009). This chapter differs from Berke and Godschalk (2009) within its scope and objective. As with this tool, I focus on plan quality analysis papers for specifically sixteen climate adaptation plans and aim to use the results to directly assist municipalities.

The second decision support tool developed is the climate adaptation and resilience outcome tool (CAROT), which aims to give stakeholders a diverse set of metrics to measure the success of climate adaptation plans. A few studies have compiled climate adaptation metrics outside municipality specific plans with the aim to assist resilience increasing projects. Donatti et al. (2020) reviewed fifty-eight ecosystem-based adaptation efforts across the globe and found a set of seven "gold standard" indicators to measure the success of adaptation outcomes including specific metrics like measuring damages and population impacted. Abt Associates (2015) also developed a list of criteria to be used to measure resilience efforts across the United States and found significant variation in measures across plans. There are also climate plans that have unique metrics for measuring their success (O'ahu Resilience Office, 2019) and sources that collect them (Resilience Metrics, 2019). The Resilience Metrics (2019) team compiled climate adaptation metrics from five plans into a large spreadsheet. The case studies came from across the United States including places like Alaska, California, Maine, New York, and New Jersey. This chapter builds upon Resilience Metrics (2019) work by adding more sources and better organizing the metrics for stakeholder use. This was done as a list of a couple of hundred metrics are not of use to Maine municipalities. The CAROT brings together a broader range of sources and is easy and efficient for resource limited communities to use.

Both tools developed from this research aim to assist Maine municipalities in their climate change adaptation efforts. These tools condense, conform, and display the wealth of scientific information regarding climate adaptation planning in a way that is more accessible to municipalities and planning teams.

2.2 Methods

2.2.1 Climate Adaptation Plan Criteria

The climate adaptation plan criteria list was constructed by doing a literature review of content analysis papers on climate adaptation plans. Content analysis is an approach used by researchers to determine if words or themes are found within a piece of writing. It is often used in plan quality analysis to rank plans using a set of criteria. These criteria are topics that if addressed in the plan would, according to the authors, lead to a "better" plan. For example, many authors consider public engagement to be an important aspect of climate adaptation. A better plan would include a proposal to engage the public in the climate adaptation process. Therefore, the authors would list criteria that should be included in a thorough plan with the goal of ranking plans by their inclusion of the various aspects. Papers were considered in this analysis if they used content analysis and specifically looked at climate adaptation plans. Natural disaster response papers were omitted from the literature review unless they specifically mentioned climate change.

The literature review started with two papers: Tang et al. (2010) "Moving from agenda to action: evaluating local climate change action plans" and Woodruff and Stults (2016) "Numerous strategies but limited implementation guidance in US local adaptation plans". These two studies came from two well respected journals, the Journal of Environmental Planning and Management and Natural Climate Change, respectively. The criteria from these papers were recorded and entered into an active spreadsheet.

Papers were then reviewed and assessed from the citations of Tang et al. (2010) and Woodruff and Stults (2016). This was then repeated for the newly pulled papers until there were no more papers that fit the scope of the analysis. The google scholar's cited by feature was then applied to Tang et al. (2010) and Woodruff and Stults (2016) using the filter "plan quality". These papers were then siphoned through and criteria were pulled from the relevant sources. The citations for these papers can be found in the appendix.

The initial list of criteria was refined using the Delphi method to narrow criteria down to a smaller, more usable, concise list. The Delphi method is a tool used by researchers that uses continuous expert feedback to narrow down and find a consensus around a given topic (Dalkey and Helmer, 1963).

The first step of the Delphi method was for individual researchers to go through and group the criteria into broad categories. This was done to give a bigger picture of the concepts experts found important in plan analysis. To further condense the list, a thorough screening process was initially done by two researchers. Each researcher independently screened through potential criteria for ones that were very similar, too specific to a certain case, or less relevant than the others with the goal to reduce the list down to less than thirty criteria. The two researchers then presented their narrowed-down criteria list to each other, refining further to converge on a revised set of criteria. The next iteration involved sharing the list with a broader set of project partners (i.e The Nature Conservancy (TNC), GOPIF, and the Maine Sea Grant), who further discussed and revised based on their knowledge of climate adaptation and municipal planning. The criteria categories were then revised to fit the remaining criteria more appropriately.

2.2.2 Climate Adaptation and Resilience Outcome Tool (CAROT)

Climate adaptation metrics measure the success of community adaptation efforts. Metrics are associated with the climate adaptation effort that is being measured (e.g climate adaptation effort = improved infrastructure, associated metric = reduced damages). There are often multiple metrics that could be used to measure the success of climate adaptation plan outcomes. This decision support tool organized climate adaptation outcomes and their associated metrics compiled from a literature review. Four sources were gathered from a general literature search for adaptation metrics. If the paper had climate adaptation outcomes and metrics, it was considered for this analysis.

Once the metrics list reached saturation and additional papers were not adding much in terms of new ideas and content, we performed the Delphi method. In comparison to the climate adaptation criteria list, metrics for the CAROT are very case specific. Therefore, the application of the Delphi method for this tool was to categorize and group similar adaptation outcomes and metrics. This organized the long list of metrics to be easier to access by stakeholders.

Two new categories were added to the metric list that represented multiple metrics. The first category was general adaptation outcome. This required going through the adaptation outcomes listed by the papers and sorting them into more broad adaptation outcomes. Following this, the metrics were grouped into broad metrics categories based on what the specific metrics were measuring (e.g metric category = businesses, metric = days of closure), to add more navigational tools to municipalities when sorting through the final metrics list.

Once the central researcher completed the task of creating new variables, another researcher validated their work to make sure categories and generalities were properly aligned. The final list included three variables: general adaptation outcome (e.g improve infrastructure), metric category (e.g businesses), and metric (e.g days of closure). This list was then compiled into an excel-based tool that filtered through each category in its respective order, producing a final list of metrics that fit the general outcome and metric category selected. The tool then went through pilot testing to eliminate programming bugs and improve user functionality.

2.3 Results

2.3.1 Climate Adaptation Plan Criteria

Sixteen peer-reviewed scientific articles establish the basis of the criteria tool. These studies resulted in four hundred and eighty-nine unique criteria that various researchers believed to be of value in climate adaptation plans. The two-hundred and seventy-six criteria were then grouped into 26 broader categories. Figure 2.1 showcases the depth of these categories and the magnitude of the initial criteria list.

After the completion of the Delphi method and expert review twenty-seven final criteria remained. This process is outlined in Table 2.1. The categories were then aggregated resulting in twelve final categories. The final criteria and categories are shown in a similar format to Figure 2.1 in Figure 2.2. Where the outer ring represents the climate adaptation criteria and the inner ring represents their respective categories. The transition between the two circle figures shows the extent to which the criteria were narrowed down through the methods. These results are also shown in an easier to read table format in Table 2.2.

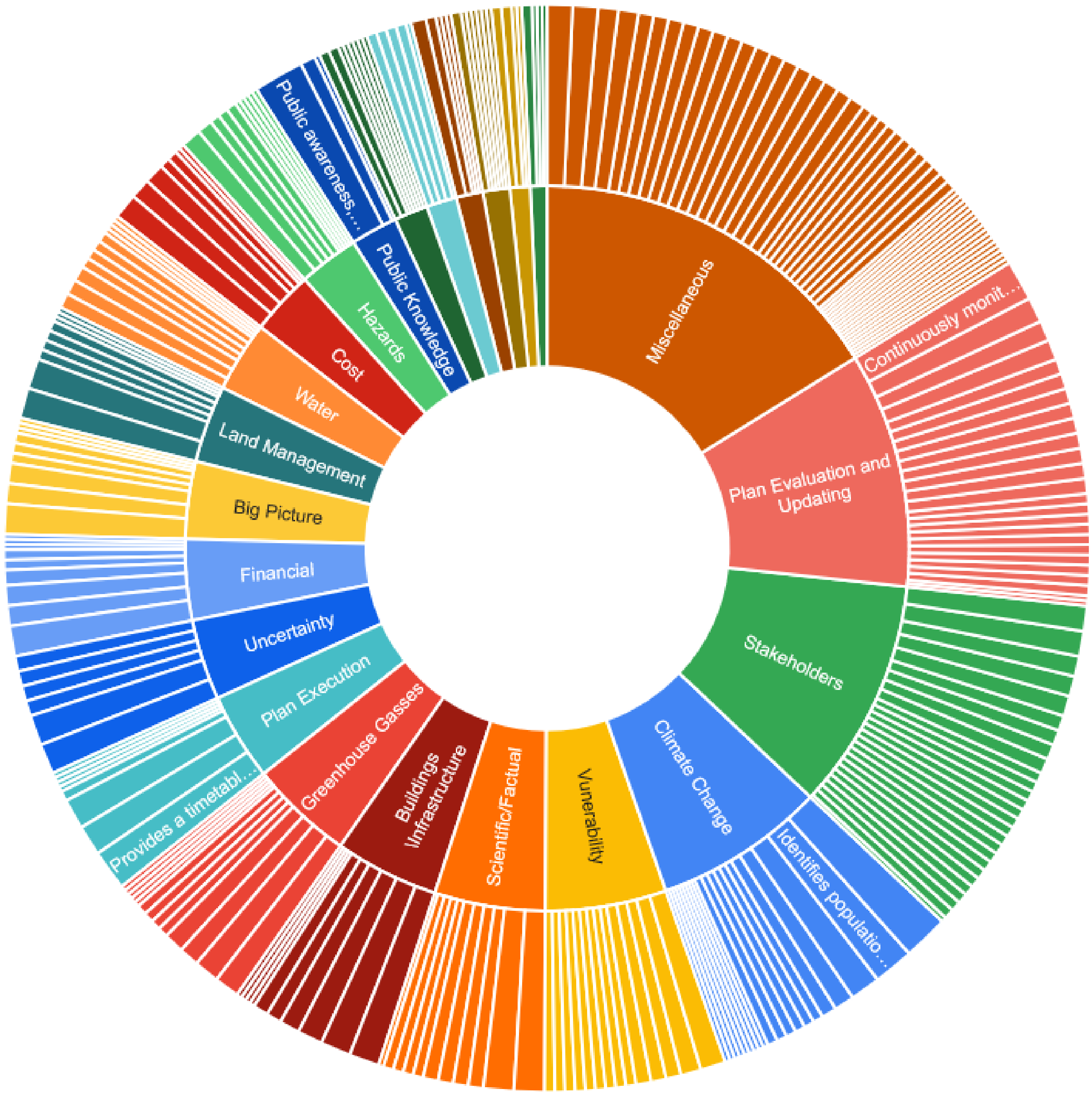

Figure 2.1. Showcase of the 276 unique criteria (outer ring) and the 26 categories they were grouped by (inner ring).

Step	Description	Number of Criteria
1	Initial Literature Review	489
2	Screening Process - Researcher 1	31
2	Screening Process - Researcher 2	23
3	Convergence	25
4	Expert Review (final list)	27

Table 2.1. The variation in criteria through the criteria list development process.

Figure 2.2. Showcase of the 27 final criteria (outer ring) and there respective categories (inner ring).

Table 2.3 showcases the degree to which different criteria categories were influenced by the initial literature review versus the Delphi method. This table does not represent the degree to which each criteria category is important, but rather gives a better picture of which criteria categories were most suggested from the literature. Categories with fewer

Criteria Category	Criteria
Stakeholder Engagement	Stakeholders most impacted are adequately represented in planning process Identify roles and responsibilities among sectors and stakeholders
Public Engagement	Public awareness, education, and participation
Vulnerability	Includes vulnerability assessment Discusses existing social, economic, environmental, or built infrastructure conditions that could lead to enhanced vulnerability in the future
Infrastructure	Provides a detailed description of infrastructure vulnerable to changing climate conditions Includes physical infrastructure strategies to prepare for climate change
Climate Change	Specific impacts of climate change for that jurisdiction Identifies specific populations that will be impacted by changing climate conditions
Equity & Community Engagement	Identifies equity concerns and prioritizes communities specific populations that are most vulnerable to changing climate conditions
Socio-economics & Cultural	Identifies socio-economic, health, and service impacts of changing climate conditions in addition to physical impacts Identifies co-benefits associated with taking adaptation action
Policy	The plan references existing policy, land use, and building codes Discusses how climate adaptation integrates into other sector policies or plans
Continuous Assessment	Includes monitoring strategies via observation or repeated measurements over time Includes planning-related strategies, including infrastructure and/or nature-based strategies that incorporate understanding of climate science, impacts, vulnerability, and risk
Uncertainty Analysis	Acknowledges uncertainties involved in projection of climate change or estimation of vulnerabilities
Plan Execution	Provides a timetable for when each action will be implemented Clear visuals, e.g., maps, charts, pictures, and diagrams Explicitly recognizes the need for flexible adaptation strategies Assigns responsibility for the implementation of each strategy Includes opportunities to build community adaptive capacity and local leadership
Funding	Clearly describes potential funding sources and associates them with particular strategies Identifies the cost estimates of implementing each adaptation strategy

Table 2.2. The final list of climate adaptation criteria, including their associated climate adaptation criteria categories.

Criteria Category	Number of Articles
Climate Change	13
Equity & Community Engagement	12
Public Engagement	12
Funding	10
Plan Execution	10
Continuous Assessment	10
Infrastructure	10
Vulnerability	10
Uncertainty Analysis	8
Stakeholder Engagement	8
Policy	6
Socio-economics and Cultural	5

Table 2.3. The criteria categories developed for this framework and the associated number of papers that referenced a criteria within that category.

mentions within literature are still thought of as important due to the list development process.

2.3.2 Climate Adaptation and Resilience Outcome Tool

Six hundred and thirty metrics were pulled from four academic, municipality, and industry sources. Some sources compiled metrics from numerous climate adaptation plans (e.g Resilience Metrics (2019)) while others were their own climate adaptation plans (e.g O'ahu Resilience Office (2019)). Accounting for this the metrics in the final list come from two-hundred and twenty-six climate adaptation plans/resilience focused projects. After the completion of the Delphi method, twenty general adaptation outcomes, forty-three metric categories, and four-hundred and eighty-eight metrics remain. The general adaptation outcomes are shown in Table 2.4. Table 2.4 gets at the diverse climate adaptation project goals that plans have aimed to measure. A link to to the tool where this information is organized can be found here.

General Adaptation Outcomes	Number of Metrics
Reduced flood risk	71
Improved community	69
Improved awareness	58
Improved planning	49
Improved ecosystem health	46
Improved emergency preparedness	33
Improved climate change mitigation	21
Improved housing resources and infrastructure	19
Reduced impacts on water quality	19
Improved recreation opportunities	17
Improved infrastructure	16
Improved engagement	13
Improved food security	12
Improved economic resilience	12
Improved resources for impacted populations	7
Improved monitoring	7
Reduced mortality, morbidity and disease	6
Improved scientific knowledge	5
Improved adaptive capacity	5
Improved zoning	3

Table 2.4. General adaptation outcomes and the associated amount of metrics for each.

2.4 Case Study

A hypothetical case study is considered to understand how these decision support tools may be applied in the field. Consider a community along the northern portion of the Kennebec River in Maine. They are a former mill town with a declining population and limited resources for climate adaptation. Their location on the river in one of the largest watersheds in the state resulted in substantial flooding damage and impacts. Because of this, numerous businesses and concerned citizens have been pressuring the town council to increase infrastructure and plan for future flood events. This section is organized into multiple subsections. These subsections are broken out by criteria categories and discuss how the criteria list can be applied to this municipality. There is also a final section which discusses how the CAROT can be applied.

2.4.1 Stakeholder and Public Engagement & Awareness

Engaging with the public who are concerned with climate adaptation is important as these are the groups to be impacted. In this example, the community should make specific efforts to engage with river side stakeholders (both populations and businesses) to ensure they are involved in the planning process as. In addition, there should be goals to involve the greater public, not within flood plains. This should involve public outreach through events and social media to educate the public on flood threats. See Table 2.5 for more information on the stakeholder and public engagement & awareness criteria.

Criteria Category	Criteria	General Overview to Compiling Categories	Inland Flooding Planning Example
Stakeholder Engagement	Stakeholders most impacted are adequately represented in planning process.	List key stakeholders to engage with, # of meetings planned, how feedback collected, and how participants compare to distribution of general population.	• Hold at least 4 stakeholder meetings. • Primarily engage with population along riverbank, most vulnerable to flooding. • Engage also with wider public to explain project and understand their views on the issue(s).
	Identify roles and responsibilities among sectors and stakeholders	List of stakeholder's roles and responsibilities, expectations, and accountability plan.	• Detailed list of stakeholders involved. • Stakeholders responsible for strengthening infrastructure have specific tasks assigned to them.
Public Engagement	Public awareness, education, and participation	List public awareness and education events and outreach plan/events. Including participation, meeting attendees, website visits etc.	• Education events of building close to flood plains and the importance of following evacuation orders during flash flood occurrences.

Table 2.5. Stakeholder and Public Engagement & Awareness

2.4.2 Vulnerability to Climate Change

Identifying how and where in a community is most vulnerable to changing climate conditions is one of the most important steps in developing a plan to make that community more resilient. Efficient adaptation requires knowing where to prioritize resources which will make the overall project more organized. In this example, the town should have their flood map updated with estimates of where flood damages will occur with the uncertainty of climate change being recognized within the estimates. Vulnerable infrastructure and populations should be labeled on the map. See Table 2.6 for more information on the vulnerability to climate change criteria.

Criteria Category	Criteria	General Overview to Compiling Categories	Inland Flooding Planning Example
Vulnerability	Includes vulnerability assessment	List different areas in town/community and their varying level of vulnerability to climate change. Includes various other information that come into vulnerability assessment for regions, e.g., population, proximity to high-risk areas, income tax, etc.	• Vulnerability assessment for inland flooding conducted and followed through to implementation (e.g., places with no infrastructure are less vulnerable even if further into the flood plain compared to places further out of flood plains with more infrastructure, also if the infrastructure import to other aspects of resilience like hospitals or fire stations)
	Discusses existing social, economic, environmental, or built infrastructure conditions that could lead to enhanced vulnerability in the future.	List key components that fall into each of the major vulnerability categories, including but not limited to social, economic, environmental, and built infrastructure. Qualitatively summarize how each category could become more vulnerable in the future without adaptation (i.e., following status quo)	• Identifies vulnerable infrastructure to inland flooding and addresses through implementation (e.g., places with no infrastructure are less vulnerable even if further into the flood plain compared to places further out of flood plains with more infrastructure, also if the infrastructure import to other aspects of resilience like hospitals or fire stations)
Infrastructure	Provides a detailed description of infrastructure vulnerable to changing climate conditions.	List of infrastructure in town/community that is vulnerable to changing climate conditions, how it is vulnerable, and to the extent at which it is vulnerable.	• Documents all infrastructure deemed vulnerable and/or upgraded via the plan. e.g., all infrastructure in 100-year flood plain (at different climate projections) is covered.
	Includes physical infrastructure strategies to prepare for climate change.	Adds solutions to the list from the previous cell when vulnerability is high enough.	• Explicitly lists infrastructure vulnerability and eventual upgrades/changes. (e.g., culvert sizes have been analyzed and culverts that cannot reach potential projections are being replaced.)
Climate Change	Specific impacts of climate change for that jurisdiction	List specific impacts of climate change in different regions of the town.	• Maps extent of flood control infrastructure put in place under various climate change impacts in 30+ years (e.g., culverts replaced, wetlands preserved, etc.)
	Identifies specific populations that will be impacted by changing climate conditions.	List mentions population numbers and demographics in the regions of the town, and qualitatively and/or quantitatively describes how each population could be affected by climate change, with and without adaptation plan implemented.	• Area and population covered from implementation of flood control measures under future climate (e.g., # of people/area ratio impacted by the implementation of culverts)

Table 2.6. Vulnerability to Climate Change

2.4.3 Community Equity, Socioeconomic, and Policy Considerations

There is more to climate adaptation planning than recognizing vulnerabilities and strengthening infrastructure. Many other community level concerns are also important. In this example, the municipality should prioritize funding to the most flood-prone groups, list co-benefits associated with planned actions, and discuss how climate policy will be implemented into current and future town level policies. See Table 2.7 for more information on the community equity, socioeconomic, and policy considerations criteria.

Criteria Category	Criteria	General Overview to Compiling Categories	Inland Flooding Planning Example
Equity & Community Engagement	Identifies equity concerns and prioritizes community's specific population that are most vulnerable to changing climate conditions.	In previously mentioned list of climate change concerns and vulnerable populations concerns specific details of equity concerns.	• Populations labeled as most vulnerable in the vulnerability assessment receive funding proportional to vulnerability (critical infrastructure associated with most vulnerable population, like culverts leading to said population are prioritizes over other culvert implication in timetable).
Socio-economics & Cultural	Identifies socio-economic, health, and service impacts of changing climate conditions in addition to physical impacts.	Lists socio-economic, health, and service impacts of changing climate conditions. These are vulnerabilities not directly related or mentioned in the infrastructure vulnerability report.	• Collects and monitors socio-demographic characteristics of affected area, focusing on income, age, race, etc. over time, identifying trends since implementation (e.g., how different socio-demographic groups are affected differently by different policy such as culverts, floodplain restoration, etc.)
	Identifies co-benefits associated with taking adaptation action.	Lists co-benefits associated with all planned projects associated with increasing resilience to changing climate conditions.	• Lists and quantifies co-benefits of implementation (e.g., Potentially revamped culverts allow for more fish passage; bridge replacement increases traffic flow, streambank protection increases housing and commercial construction).
Policy	The plan references existing policy, land use and building codes	Lists current policy, land use, and building codes impacted by previously stated projects.	• Implementation builds off existing policy / codes as close as possible to ensure efficiency (e.g., Culvert sizes suggestions have been updated to fit climate projections.)
	Discusses how climate adaptation integrates into other sector policies or plans	Lists how climate adaption plans integrate into other policies and plans in town's code.	

Table 2.7. Community Equity, Socioeconomic, and Policy Considerations

2.4.4 Science-based and Uncertainty Assessment

Using scientifically rigorous methods in the development of a climate adaptation plan is important as climate change is a complex and hard to predict phenomenon that can have estimation uncertainties. In this example, the town should prepare for the upper bound (i.e, most extreme) of probable future flood plains when designing flood resilient infrastructure. They should also select metrics to measure the success of their climate adaptation efforts. These metrics are to ensure plan goals are being reached and are on schedule. See Table 2.8 for more information on the science-based and uncertainty assessment criteria.

Broad Indicator	Detailed Indicator	General Overview to Compiling Indicator	Inland Flooding Planning Example
Continuous Assessment	Includes monitoring strategies via observation or repeated measurements over time.	Detailed list of monitoring strategies over time to see if previously mentioned projects are effective at increasing resilience to climate change.	• Identifies and collects quantitative metrics over time, e.g., number of houses/infrastructures in flood prone areas does not increase from time A to B.
	Includes planning-related strategies, including infrastructure and/or nature-based strategies that incorporate understanding of climate science, impacts, vulnerability, and risk.	Lists key strategies and/or infrastructure changes to consider improving resilience. Each strategy is supported by qualitative and/or quantitative info regarding the science, impacts, vulnerability, and risk from implementing said option.	• Strategies implemented mitigate risk of flooding, are cost-effective, and protect diverse populations in community (e.g., culvert, price of culvert. people impacted or wetland restoration, price of wetland restoration, people impacted.)
Uncertainty Analysis	Acknowledges uncertainties involved in projection of climate change or estimation of vulnerabilities	Climate impact projections are presented in ranges due to uncertainties involved. Planned actions are cost-efficient but account for higher range of estimates.	• Implementation meets expectations of future climate impacts, with buffer / contingency for uncertainty in projections. (e.g., flood plain areas considered, or culvert size based on different climate projections.)

Table 2.8. Science-based and Uncertainty Assessment

2.4.5 Plan Execution and Funding

Fully developing a project plan is only half of the battle. Plan execution is just as important as the planning itself, and a perfect plan with poor execution can have a detrimental effect on the effectiveness of the climate adaptation project. Timely and efficient plan execution requires writing timelines, visuals, and funding strategies directly into the plan to ensure the execution of actions. For this example, the town should have a timeline for when tasks should be completed, responsible parties for completing the tasks, assisting visual aids (e.g maps, pictures, and diagrams), and funding sources for each task. The inclusion of these items will help ensure the plan is executed on time. See Table 2.9 for more information on the plan execution and funding criteria.

Broad Indicator	Detailed Indicator	General Overview to Compiling Indicator	Inland Flooding Planning Example
Plan Execution	Provides a timetable for when each action will be implemented.	Proposed actions have a timetable of when tasks need to be completed.	• Each planned actions has a timetable of when specific tasks need to be done to complete task on time.
	Clear visuals, e.g., maps, charts, and pictures, and diagrams	Good use of maps, charts, pictures, and diagrams to properly explain climate projections in specific critical areas and actions.	• Produce maps, data, and figures of where and what needs to be implemented (e.g., location, size, # of culverts)
	Explicitly recognizes the need for flexible adaptation strategies.	Qualitatively lists how the adaptation strategies are flexible and can be adapted further, if required.	• Adaptation strategies are flexible and can be adjusted if estimates of flooding risks change.
	Assigns responsibility for the implementation of each strategy.	Each step in timeline assigns responsibility for who is supposed to complete steps.	• Each planned action in timeline has the associated part responsible for completing action.
	Includes opportunities to build community adaptive capacity and local leadership	Lists specific opportunities for adaptation plan/project to build community adaptive capacity and local leadership	• Highlights opportunities and steps that plan can take to build capacity.
Funding	Clearly describes potential funding sources and associates them with particular strategies.	Each action in plan has been attributed with potential/actual funding sources.	• Lists sources of funding used for each step-in timeline (e.g., where funding came from, if it was adequate for different resilience projects).
	Identifies the cost estimates of implementing each adaptation strategy.	Cost estimates included in each step of timetable.	• Each step in timeline has an associated estimated cost.

Table 2.9. Plan Execution and Funding

2.4.6 Use of the CAROT

To ensure the satisfaction of the "Continuous Assessment" portion of the climate adaptation criteria list, climate change adaptation practitioners should develop case specific metrics for their municipalities to ensure plan goals are being reached. In this specific case, the municipality is interested in measuring their success at reducing flood risks for their many businesses as a part of their plan.

They use the CAROT to find example metrics to build their climate adaptation success plan. The practitioner would select the general climate adaptation outcome of interest, in this case, being reduced flood risk (Figure 2.3). Following this step, they would select the appropriate metric category, in this case being "Business" (Figure 2.4). Once the initial two boxes are selected the tool will output metrics fitting the previous choices (Figure 2.5). For this example, the town could decide to use "avoided economic losses" as a broad metric and "avoided days of closure" as a more specific hazard mitigation success measurement. The municipality would then include these metrics within the plan and would assess how they change over time with the implementation of resilience increasing projects.

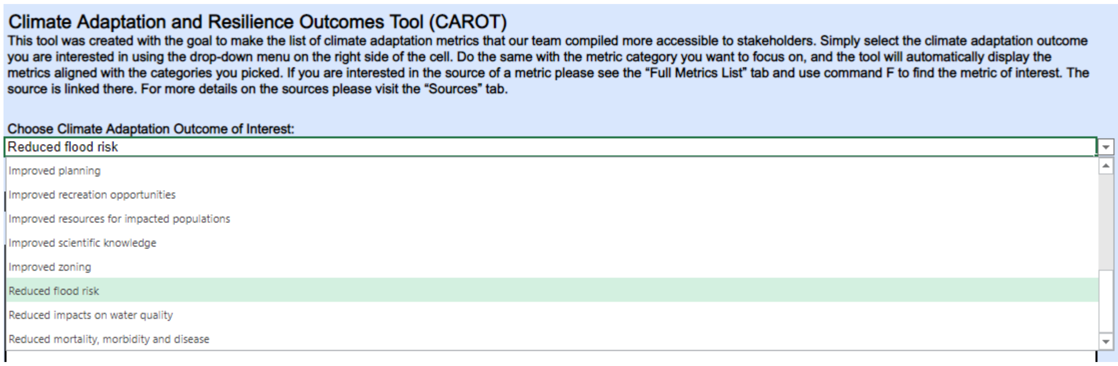

Figure 2.3. Selection of the general adaptation outcome.

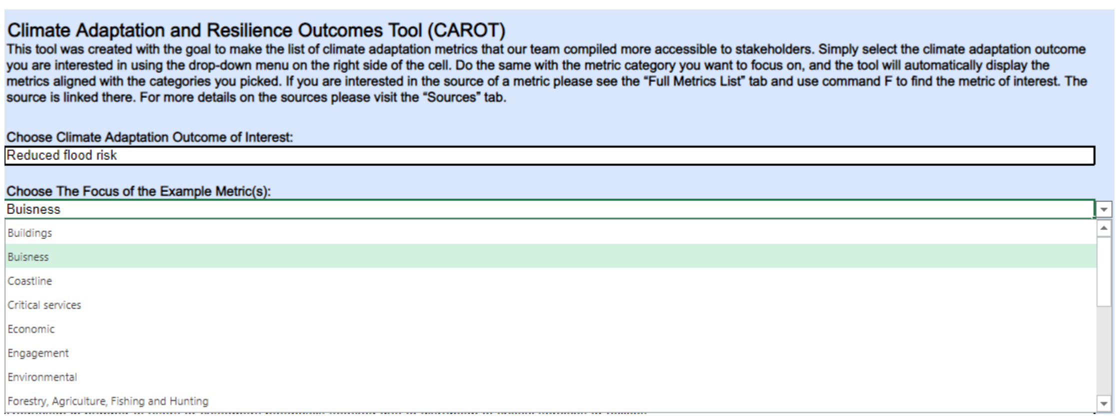

Figure 2.4. Selection of the metric category.

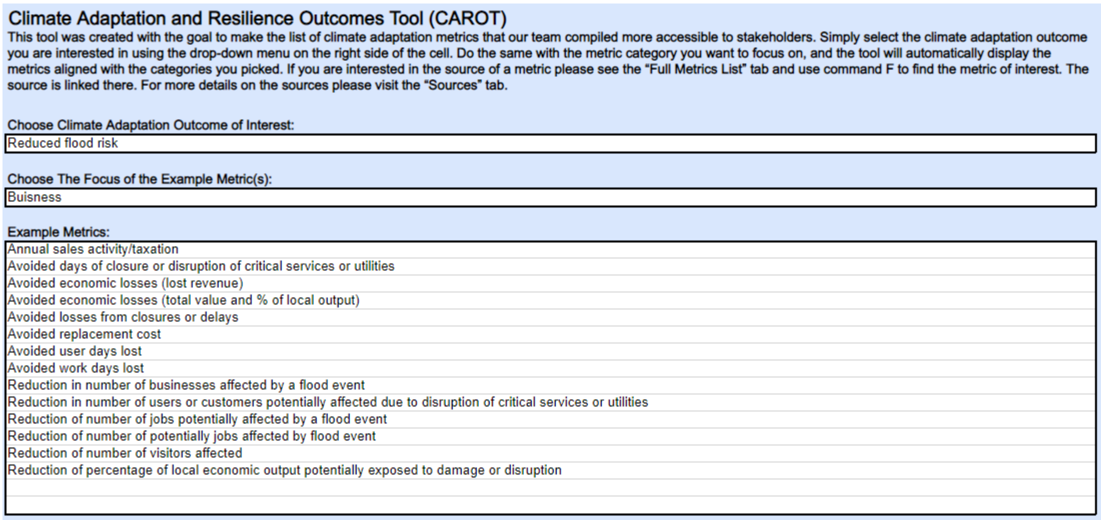

Figure 2.5. Output of metrics from the initial two categories selected.

2.5 Discussion

Two decision support tools discussed in this chapter were developed via two literature reviews and the Delphi method. Both of these tools give insight into the vast range of topics required to produce, implement, and measure the success of climate adaptation plans. They also highlight that successful climate adaptation requires much more than just infrastructure improvements which is often the initial thought. Rather climate adaptation requires the need for spreading awareness, diverse stakeholder involvement, specific engagement with equity, and increasing socio-economic status to name a few. Preparing for climate change can be a complex, daunting task for municipalities especially given the intricacy required for thorough adaptation. However, the tools presented in this research can make the goals and objectives of climate adaptation more clear for resource limited municipalities in Maine.

The climate adaptation plan criteria list (i.e tool 1) is best designed to help municipalities develop a thorough climate adaptation plan. While the tool was developed specifically for Maine municipalities, all portions are applicable to a more broad geographic area. The tool is useful for climate adaptation plan development and by extension, could also be used for plan quality analysis studies as well as for measuring the success of this tool across Maine.

The CAROT (i.e tool 2) aims to assist municipalities in the continuous assessment aspect of the criteria list. It gives examples of how others have measured the success of their climate adaptation plans and adapts these metrics for easy access by Maine municipalities. Both tools complement each other with overlapping topics of importance to climate adaptation. In comparison to the criteria list, the CAROT should be less of a guide and more of an example of the metrics others have used. Further, selected metrics should be case specific for the most effective measuring of climate adaptation in a given place or context. Similar to the climate adaptation plan criteria list, this tool was specifically made for Maine municipalities. However, there are no aspects that would make it only applicable to Maine, suggesting this tool can be used outside the state.

A limitation of this research is the subjectivity of the Delphi method. If a separate team of researchers was to repeat the steps in the methods they would likely result in a similar initial list as this research. However, the narrowed down categorization would likely be significantly different. Decisions about which criteria should stay, which should be merged, and how metrics should be grouped originated from research decisions rather than systematic methodology. The Delphi method was used to reduce this inherent bias in this crucial step to create the most objective lists possible. Despite this, there was no avoiding the subjectivity of the matter due to the nature of the method.

Future research based on the climate adaptation criteria list should focus on using the list to assess how well climate adaptation plans across the United States line up with academic researchers' reasoning. In terms of the CAROT, more metrics could be added to the list once more climate adaptation plans with continuous assessment are published to research accessible spaces. More types of organizations could be experimented with an increased sample of studies. For example, study specific metrics such as region or spatial size of the project could be used, as they are traditionally less biased than the categorization used in the CAROT.

2.6 Conclusion

Climate change preparedness is of large concern in the context of resilience building at a community level. This work is the extension of a framework developed to aid climate change adaptation planning and implementation in municipalities across the state of Maine. Two decision support tools were constructed, the "climate adaptation criteria" list and the "climate adaptation and resilience outcome tool (CAROT)". Both tools were constructed through independent literature reviews and the Delphi method to make the wealth of knowledge of climate adaptation planning in the literature more accessible and useable at a municipality level. The broad nature of these tools facilitates use across several climate adaptation projects, goals, and objectives. This research stresses the importance of creating more encompassing climate adaptation plans for specific municipalities, while also aiming to make the process of developing climate adaptation plans easier, especially for resource limited communities.

APPENDIX A

CHAPTER 1

A.1 Resilience Metrics Literature Review

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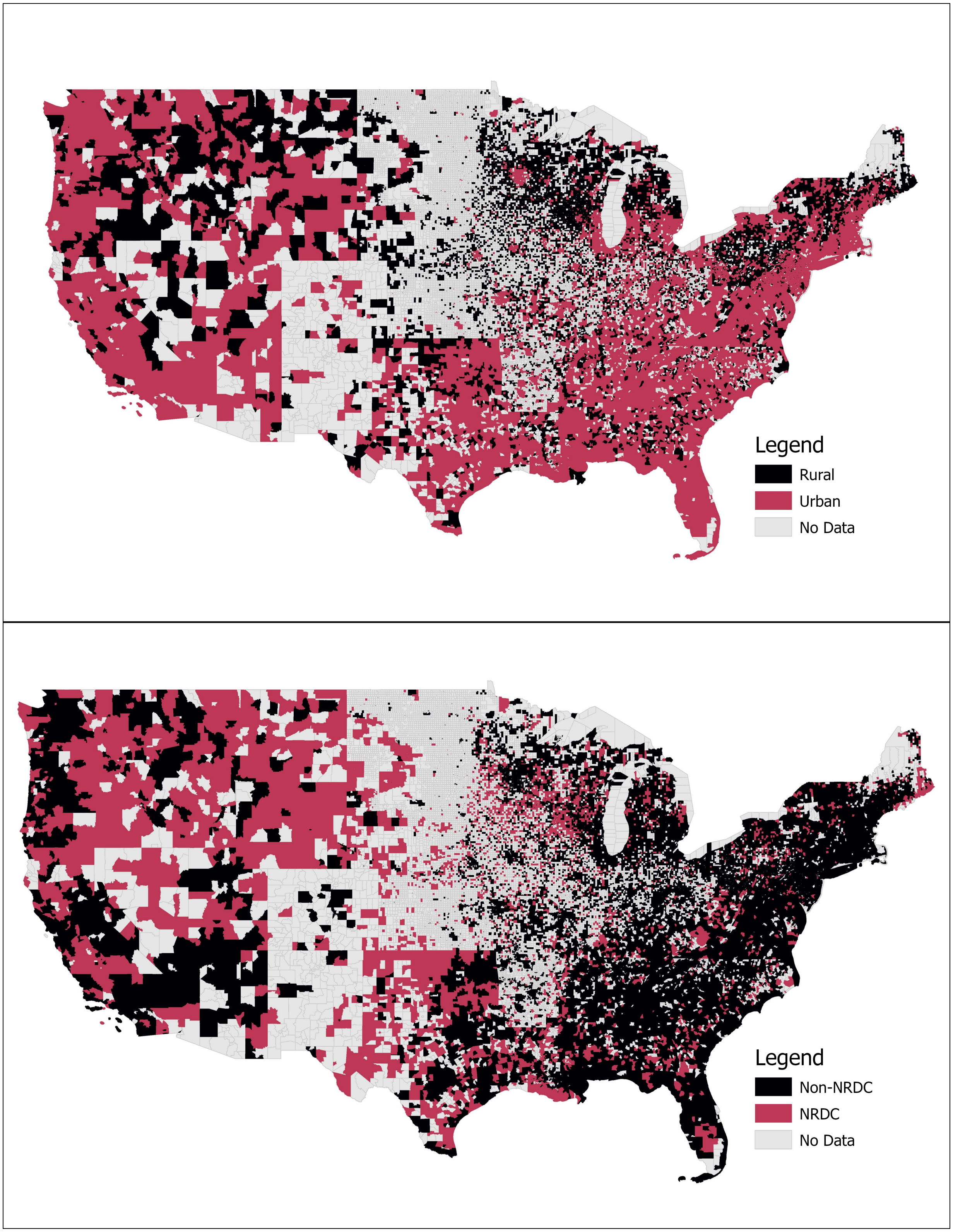

Figure A.1. Distribution of urban/rural and NRDC/Non-NRDC across the United States for county subdivisions included in the analysis.

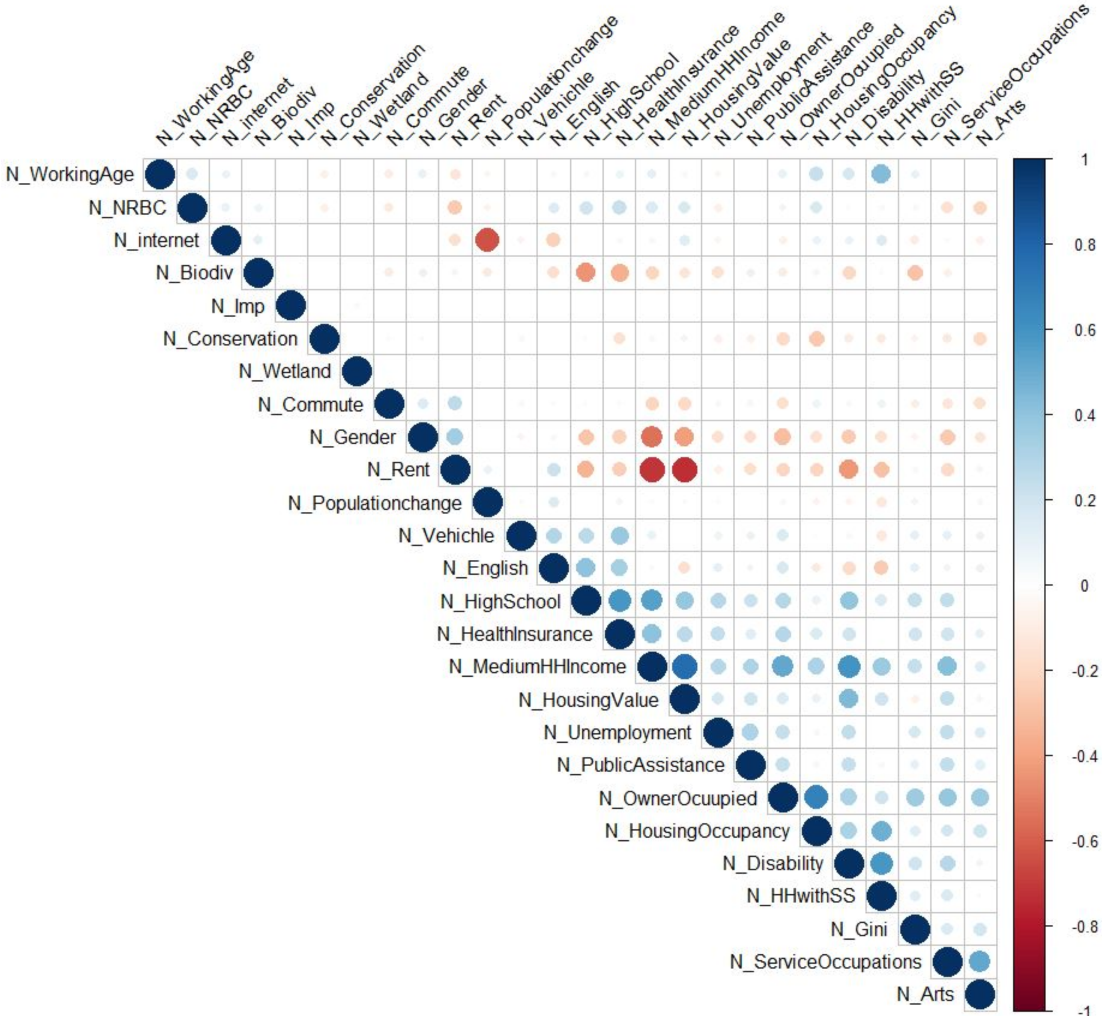

Figure A.2. Correlation's between the variables in the community resilience index.

Indicator	Number of Studies	Domain
Unemployment rate	7	Economic
High school graduates	5	Social
People below poverty level	5	Social
Medium household income	4	Economic
Owner-occupied housing	4	Housing
Household with no vehicle available	4	Housing
Health insurance coverage	3	Social
Median monthly gross rent	3	Housing
Per capita income	3	Economic
People who speak English "less then well"	3	Social
Population change	3	Social
Housing in structures with 10 or more units	3	Housing
More people then rooms (crowding)	3	Housing
Civilian noninstitutionalized population with a disability	3	Social
Single parent households with children under 18	3	Social
Employed in natural resource occupation	3	Economic

Table A.1. Metrics that were used by 3 or more papers in the literature review.

Indicator	Justification
Working age population (ages 20-65)	A larger working age population is generally healthier, more productive, and therefore more resilient.
Health insurance coverage	More health insurance coverage leads to a healthier population that is more resilient.
Population with high school degrees	A more educated population the will have more economic prosperity and skills available.
People who speak English "less than well"	A larger English speaking population will more easily be able to participate in government operations and social constructs.
Population change 2000-2018	Large population losses or gains puts strain on communities.
Mean advertised max broadband download speed	Better internet infrastructure can lead to more education and economic opportunities.
Unemployment rate	Large unemployment in a community indicate less economic opportunities.
Median household income	Low levels of income in a community indicate poor economic opportunity.
Mean commuting time	Long commuting times suggest poor economic opportunities within the community.
Service occupations	Studies suggest communities highly dependent on service occupations are less resilient.
Arts; entertainment; and recreation; accommodation & food services	Studies suggest communities highly dependent on arts; entertainment; and recreation; accommodation & food services are less resilient.
Households with social security	A large reliance on government programs indicates lower levels of resilience. Also indicative of the amount of the population who is either disabled or retired.
Households with public assistance income	A large reliance on government programs indicate less economic productivity and community self reliance.
Gini index of income inequality	Large income inequality is often causation of other socio-economic issues in a community.
Gender income inequality	Large gender income inequality is often indicative of other socio-economic issues in a community.
Owner-occupied housing	Low owner-occupied housing suggests many rental units and less self reliance within a community.
Households with no vehicle available	Vehicle's allow community members to reach importance services.
Median housing value	Larger housing values suggest better, more resilient property conditions.
Housing occupancy rate	A low housing occupancy rate suggests more abandoned housing and an unhealthy housing stock.
Median monthly gross rent	High rent prices indicate high costs of living which puts stress on communities.
Land in wetland	Proxy for natural flood buffers.
Percent impervious land	Impervious surfaces cause increased temperatures and decreased water quality.
Public open space (parks, community forest, etc.)	Conserved spaces generate numerous provisioning, regulating, and cultural, ecosystem services for communities.
Recognized biodiversity value	Biodiverse areas have stronger provisioning ecosystem services.

Table A.2. Justification for the inclusion of each metric.

ACS 5-year Estimate Metric	Missing Observations
Human well-being/cultural/social indicators	
Working age population (ages 20-65)	476
Health insurance coverage	476
Population with high school degrees	488
People who speak English "less than well"	476
Population change 2000-2018	0
Economic/financial indicators	
Unemployment rate	1434
Median household income	2678
Mean commuting time	3335
Service occupations	706
Arts; entertainment; and recreation; accommodation & food services	706
Households with social security	485
Households with public assistance income	485
Gini Index of Income Inequality	955
Gender income inequality	4588
Infrastructure indicators	
Owner-occupied housing	360
Households with no vehicle available	485
Median housing value	3019
Housing occupancy rate	360
Median monthly gross rent	9563

Table A.3. Data loss per each ACS metric. Many county subdivisions that had some missing values overlapped with others.

APPENDIX B

CHAPTER 2

B.1 Climate Adaptation Criteria List Sources

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